NORDITA - 95/53 P

hep-ph/9507367

THE INTERPRETATION OF RAPIDITY GAPS AT HERA

Paul Hoyer and C. S. Lam*

NORDITA, Copenhagen, Denmark

ABSTRACT

In leading twist deep inelastic ep scattering, the virtual photon interaction is fast compared to the time scale of soft color rearrangement. We compare the Pomeron exchange model, in which a neutral cluster is preformed, with a gluon exchange model, in which color is exchanged after the hard interaction. We find several features of the DIS data and of data on exclusive hard processes that favor a gluon exchange scenario. If correct, the postulate of soft color interactions between the produced $(q\bar{q})$ system and the target has important implications for other processes. In particular, this may explain the puzzles of charmonium hadroproduction.

*Permanent address: McGill University, Montreal, Canada

1 Introduction

The discovery at HERA [1, 2, 3] of Deep Inelastic Scattering (DIS) events with a large rapidity gap between the particles produced in the target (proton) and current (virtual photon) fragmentation regions raises interesting questions concerning the principles of color neutralization in hard scattering. The data rather convincingly demonstrate that the gap events are of leading twist, *i.e.*, they are not power suppressed at large photon virtualities Q^2. Hence the virtual photon scatters off single quarks and gluons in the target proton.

In leading twist scattering, the transverse momenta of the final state partons are of $\mathcal{O}(\mathrm{Q})$. Since they eventually combine to color singlet hadrons, there must be color exchange between the produced partons and the proton remnant. This non-perturbative process is usually modelled in terms of color strings. As two partons connected by a string fly apart, the string breaks repeatedly and the rapidity interval between the partons is populated with hadrons. Albeit heruristic, this picture has been tested extensively and successfully, especially in e^+e^- annihilations (where no large rapidity gaps are observed).

In DIS the virtual photon takes a "snapshot" of the proton wave function – for $Q \gg \Lambda_{QCD}$ nonperturbative color exchange processes which last 1 fm or longer are easily resolved. There are thus two principal scenarios for the creation of rapidity gaps: The formation of color neutral clusters can take place either *before* or *after* the hard scattering. In the 'Pomeron exchange' model [4, 5] the virtual photon scatters off a preformed color neutral cluster (the Pomeron). In the 'Gluon exchange' models [6, 7] the initial hard scattering is quite similar in events with and without gaps. Following a standard hard scattering $\gamma^* g \to q\bar{q}$, secondary soft gluon exchange in the color field of the target is postulated to transform the octet $q\bar{q}$ pair into a color singlet.

In this paper we want to discuss and compare these two quite different approaches to gap dynamics. After a brief review of each model, we discuss their consequences for several types of hard scattering, and compare with available data. Naturally, neither of the models is likely to be fully correct, but they represent the two main options for understanding the data. Related models for the rapidity gaps in hard scattering processes are given in [8]. For a recent review of hard diffraction and rapidity gaps see Ref. [9].

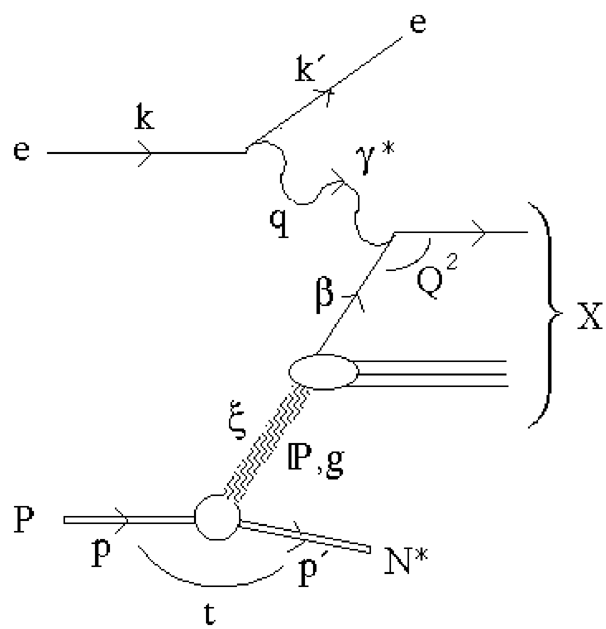

Figure 1: Kinematics of the process $e(k)+p(p) \to e(k')+N^*(p')+X$. $q^2 = (k-k')^2 = -Q^2$; $x_{Bj} = Q^2/2q\cdot p$; $t = (p-p')^2$; $\xi = q\cdot(p-p')/q\cdot p$; $\beta = Q^2/2q\cdot(p-p')$.

2 Two scenarios for DIS gaps

The two types of models we shall consider are based on very different dynamics, but their kinematics can be depicted using the same diagram (Fig. 1) for the measured process $ep \to eN^*X$. In the present HERA data the proton fragment N^* (which may be a single nucleon) is not detected. A rapidity gap is required between the proton beampipe (which contains the

N^*) and the hadrons comprising system X. The constraint that all particles in N^* escape detection limits the momentum transfer at the nucleon vertex ($|t| \lesssim 7$ GeV^2) [2] and mass of the proton fragment ($M_{N^*} \lesssim 4$ GeV) [3].

Depending on the model, the proton emits either a Pomeron ($I\!P$) or gluon (g), which carries a small fraction ξ of the proton momentum. The photon then scatters on a parton carrying a fraction β of the Pomeron or gluon momentum. Assuming $|t| \ll Q^2, M_X^2$ both ξ and β can be reconstructed from the measured quantities $x_{Bj} = \xi\beta$ and $M_X^2/Q^2 = (1-\beta)/\beta$.

The two-step process of Fig. 1 implies that the measured "diffractive" structure function for events with rapidity gaps can be expressed as a product

$$F_2^{gap}(x_{Bj}, Q^2, \beta) = f_{i/p}(\xi, Q^2) F_2^i(\beta, Q^2) \tag{1}$$

Here $f_{i/p}(\xi, Q^2)$ represents the probability for finding the emitted object ($i = I\!P$ or g) in the proton, while $F_2^i(\beta, Q^2)$ is the structure function of this object. The dependence on Q^2 should be weak (at most logarithmic) and an average has been taken over the (unmeasured) virtuality t of the Pomeron or gluon.

The HERA data [2, 3] is consistent with the factorization (1), and allows a separate measurement of the functions $f_{i/p}$ and F_2^i.

2.1 Pomeron exchange

The possibility of hard scattering on the Pomeron was proposed long before the evidence for rapidity gaps at HERA [4, 5]. Soft diffractive hadron-hadron scattering can be modelled by the exchange of a Regge trajectory with vacuum quantum numbers. If this Pomeron corresponds to an actual quark-gluon cluster in the hadron wave function then it serves as a target for the virtual photon and will give rise to DIS events with a rapidity gap.

Using Pomeron factorization, the momentum distribution $f_{I\!P/p}$ in Eq. (1) can be obtained from analyses of soft proton scattering. It should be independent of Q^2 and (at $t=0$) its dependence on $\xi = x_{I\!P}$ should be [10, 11]

$$f_{I\!P/p}(x_{I\!P}, Q^2) \propto {x_{I\!P}}^{1-2\alpha_{I\!P}(0)} \tag{2}$$

where $\alpha_{I\!P}(0) \simeq 1.08$ is the intercept of the Pomeron Regge trajectory. The data on soft scattering does not constrain the Pomeron structure function $F_2^{I\!P}(\beta, Q^2)$. The basic assumption that the Pomeron is factorizable leads to quite powerful predictions for a number of hard processes. We return to these below.

2.2 Gluon exchange

It is possible that the presence or absence of rapidity gaps in DIS is determined by soft gluon dynamics long ($\mathcal{O}(1$ fm) in the target rest frame) after the hard scattering [6, 7]. Since the rapidity gaps are observed at small values of $x_{Bj} \lesssim 0.01$, a large fraction of the hard scattering is due to $\gamma^* g \to q\bar{q}$. The function $f_{i/p}(\xi, Q^2)$ in Eq. (1) should then be identified with the gluon momentum distribution $g(x_g, Q^2)$ of fully inclusive DIS, with $\xi = x_g$. The quark distribution in gluons $F_2^g(\beta, Q^2)$ is to leading order in $\log Q^2$ given by the $g \to q\bar{q}$ splitting function [6].

In this scenario the $q\bar{q}$ pair, which is produced as a color octet, can turn into a singlet while passing through the color field of the target. In this case no color string is stretched to the proton remnant, and a rapidity gap is created. Assuming a statistical probability $P_1 \simeq 1/9$ for the $q\bar{q}$ to emerge as a singlet, Buchmüller and Hebecker [6] found good agreement with the cross section and kinematic distribution of rapidity gaps observed at HERA. The more detailed Monte Carlo model of Ref. [7] was also found to agree with the data.

It is important to note that the $q\bar{q}$ pair is formed at transverse size $r_\perp \simeq 1/Q$, and expands with a velocity $v_\perp$ of $\mathcal{O}(Q/\nu) \ll 1$ in the proton rest frame. Hence the pair remains compact while traversing the target and as a color octet it interacts with soft target gluons. If such interactions can indeed turn the quark pair into a color singlet then this has important consequences for many other hard processes, including charmonium production. We return to these below.

3 Tests in hard diffraction

3.1 DIS gap events

Many comparisons of the above (and related) models with data on DIS gap events have recently been made [2, 3, 6, 7, 8, 9, 12, 13]. We note the following.

3.1.1 ξ-dependence

According to Eq. (2), Pomeron exchange predicts that the diffractive structure function (1) is proportional to ${x_{I\!P}}^{-1.17}$ at small $x_{I\!P} = \xi$ for all Q. For gluon exchange, the behavior should be given by the gluon distribution, $\xi = x_g$ with

$$g(x_g) \propto x_g^{-a_g} \tag{3}$$

The effective power a_g found in analyses of scaling violations in DIS [14, 15, 16] is in the range $a_g = 1.22 \ldots 1.35$ for $Q^2 = 4 \ldots 7$ GeV^2, and increases with Q^2.

The ξ-dependence of the measured structure function (1) for events with rapidity gaps has been parametrized as $f(\xi) \propto \xi^{-a_{gap}}$. Averaged over $Q^2 > 8$ GeV^2 the result was

$a_{gap} = 1.19 \pm .06(stat) \pm .07(syst)$ for the H1 data [2] and $a_{gap} = 1.30 \pm .08(stat) {}^{+\,.08}_{-\,.14} (syst)$ for the ZEUS data [3]. In a direct determination of the gluon structure function using (2+1) jet events, H1 obtained [17] for the gluon structure function (3) an effective power $a_g = 1.63 \pm .12$ at $Q^2 = 30$ GeV^2. Interestingly, in this analysis the fraction $(8 \pm 2)\%$ of events with a rapidity gap was consistent with being independent of x_g in the measured range $.0019 < x_g < .18$.

Taken together, the ξ-dependence of the HERA gap events suggests a somewhat steeper increase at small ξ than expected for Pomeron exchange, and is consistent with the gluon exchange model.

3.1.2 β-dependence

The measured structure function for DIS gap events, Eq. (1), is weakly dependent on β [2, 3].This is in qualitative agreement with the gluon exchange model. For Pomeron exchange further assumptions must be made to predict the β-dependence.

3.1.3 t-dependence

For Pomeron exchange the $I\!PpN^*$ vertex should be the same as the one measured in soft hadron scattering. In particular elastic recoil ($N^* = p$) should dominate inelastic. The t-dependence for elastic recoil should be given by the proton form factor [10, 11].

In the gluon exchange model one expects the gluon virtuality to grow with Q^2 as usual in DIS (in contrast to the Pomeron, whose virtuality is independent of Q^2). However, the gluon momentum fraction x_g is quite small for the gap events. A gluon with $x_g = .01$ (close to the upper experimental range) and virtuality 1 GeV^2 is separated from the proton by 4.6 units of rapidity. Hadronic fragments associated with gluons in this rapidity range will typically be grouped with system X in Fig. 1, rather than with the N^*. The removal of such a wee gluon from the proton (followed by color compensation from soft gluon exchange) may imply a dominance of elastic recoil ($N^* = p$) also in the gluon exchange model. Nevertheless, the prediction is less precise than for Pomeron exchange.

3.2 Hard exclusive diffraction

Both the Pomeron and gluon exchange models, if correct for DIS gap events, have implications for hard exclusive processes as well. This follows directly from Pomeron factorization and, in the gluon case, from the fact that the produced $q\bar{q}$ system remains compact while traversing the color field of the target.

3.2.1 s-dependence

The $\gamma p \to J/\psi\, p$ cross section has been found [18] to grow considerably with energy in the range 12 GeV $\leq E_{CM} = \sqrt{s} \leq$ 114 GeV. Parametrized as $\sigma \propto s^\lambda$, the effective exponent $\lambda \simeq .36 \pm .04$ is considerably larger than the $\lambda \simeq .08$ expected for Pomeron exchange. A perturbative QCD calculation [19, 20] involving two hard gluon exchanges predicts the cross section to increase like the square of the gluon structure function, $[xg(x, m^2_{J/\psi})]^2$ with $x \simeq m^2_{J/\psi}/s$. According to Eq. (3) this would imply that $\lambda \simeq 2(a_g - 1) \simeq 0.44 \ldots 0.70$, which is rather larger than the measured value, but consistent considering the uncertainties. The gluon exchange model [6, 7] for DIS gap events implies that only one gluon is perturbative, hence $\lambda \simeq a_g - 1$, closer to the data.

Recently, the $\gamma^* p \to \rho\, p$ cross section was measured in the HERA energy range [21]. While the cross section increases only moderately with energy at $Q^2 = 0$, as expected for

Pomeron exchange, the increase is much faster at $Q^2 = 8.8$ GeV^2 and $Q^2 = 16.9$ GeV^2. The conclusions are quite analogous to those given above for J/ψ production.

3.2.2 A-dependence

The nuclear target dependence of the cross section for incoherent ρ meson electroproduction has been parametrized as

$$\sigma_{incoh}(\gamma^* A \to \rho A) \propto A^{\alpha(Q^2)} \tag{4}$$

The exponent has been found [22] to increase from $\alpha(0) \simeq 2/3$ to $\alpha(5 \text{ GeV}^2) \simeq 0.9$. This behavior is expected on the basis of 'color transparency' [23], according to which a transversally compact color singlet $q\bar{q}$ pair has a small reinteraction probability in the nucleus.

It is a consequence of Pomeron factorization that all A-dependence of the $\gamma^* A \to \rho A$ process must come from the $I\!PAA$ vertex, which is independent of Q^2. The observed Q^2-dependence of the power α in Eq. (4) thus breaks Pomeron factorization.

In the gluon exchange model [6, 7] the $q\bar{q}$ pair is for high Q^2 created as a compact color octet which does interact repeatedly with the color field of the target nucleus. Since little momentum is transferred in these soft interactions, the nucleus is nevertheless effectively transparent to the pair. Hence the effective power is $\alpha \simeq 1$ at large Q^2, as observed. Note that for the nucleus A to stay intact it is important that the soft scattering can restore the color to the nucleon from which it was removed by the initial perturbative gluon. This is possible since the longitudinal momentum transfer in the rest frame of the nucleus is very small, of $\mathcal{O}(\Lambda^2_{QCD}/s)$. The soft scattering is thus longitudinally coherent over the whole nucleus.

The cross section for incoherent J/ψ photoproduction has an A-dependence corresponding to Eq. (4) with $\alpha(m^2_{J/\psi}) \simeq 0.9$, [24, 25] which agrees well with the power obtained for ρ electroproduction. For the J/ψ process the A-dependence is known also for the coherent part of the cross section,

$$\sigma_{coh}(\gamma A \to J/\psi A) \propto A^{\alpha_{coh}} \tag{5}$$

with $\alpha_{coh} = 1.40 \pm .06 \pm .04$ measured by E691 [24] and $\alpha_{coh} = 1.19 \pm .02$ obtained by NMC [25].

For a factorizable Pomeron one would again expect $\alpha_{coh} \simeq 2/3$, as observed in soft coherent scattering.

For a compact $q\bar{q}$ pair with a small (effective) reinteraction probability in the nucleus, the forward ($t = 0$) scattering is coherent over the whole nucleus, and thus the forward cross section is proportional to A^2. The requirement of coherence in the transverse direction implies a steepening of the forward peak with increasing A, reducing the power to $\alpha_{coh} = 2 - 2/3 = 4/3$ for the full reaction cross section. This value is in reasonable agreement with the power measured in the E691 and NMC experiments [24, 25].

4 Hadroproduction of quarkonia

The gluon exchange model [6, 7] for DIS rapidity gaps postulates that transversally compact $q\bar{q}$ pairs experience repeated soft color interactions in the target. If correct, this has important consequences also for the hadroproduction of heavy quarkonia. According to perturbative QCD (more precisely, in the 'color singlet model' [26]) quarkonia with charge conjugation $C = -$ (such as the J/ψ) are produced in subprocesses like $gg \to J/\psi g$. The extra gluon emission is required by the quantum numbers of the J/ψ, and significantly reduces the cross section compared to that for $C = +$ states like the χ_2 ($J^{PC} = 2^{++}$), which are directly created through $gg \to \chi_2$.

As a matter of fact, the perturbative calculations seriously underestimate the J/ψ and ψ' cross sections, whereas the prediction for χ_2 is consistent with the measurements [27, 28, 29]. Most importantly, the discrepancies appear [30] to be as large for the bottomonium states (Υ) as for the charmonia – the new effect is leading twist in the quark mass.

A $q\bar{q}$ pair which interacts repeatedly in the color field of the target will not retain the quantum numbers of the initial perturbative gluons. Hence there is no need for the emission of a perturbative gluon in the production of $C = -$ states, and the cross sections of all charmonia are comparable. This agrees with the trend of the data.

Note that a solution of the quarkonium hadroproduction puzzle along these lines is quite different, in principle, from that of the 'color octet' model [31]. In the octet model, the gluon emitted in the final state is related to the higher Fock states of the quarkonium. The emission happens after a characteristic time in the rest frame of the quarkonium, hence typically long after the heavy quarks have left the target. A minimal number of such gluons are emitted, having a hardness related to the radius of the charmonium state. The importance of this effect should decrease with the mass of the heavy quark.

A further indicator of the dynamics of charmonium hadroproduction is provided by the experimental observation that the J/ψ [32] and ψ' [33] are produced unpolarized. In both the color singlet [29] and color octet [34] models a transverse polarization is predicted. A random color field may destroy the initial polarization of the heavy quarks. An analogous effect of the vacuum color field on the polarization of the annihilating quarks in the Drell Yan process has been discussed in Ref. [35].

5 Summary

We have compared two alternative scenarios for the dynamics of rapidity gaps in the final states of deep inelastic ep collisions. The main distinguishing characteristic of the two approaches is the time of formation of the color singlet clusters (which are widely separated in rapidity). In the Pomeron exchange model [4, 5] the virtual photon scatters off a preformed neutral cluster. In the gluon exchange model [6, 7] the hard scattering is the same in events with and without gaps, and color is exchanged afterwards. Both models have been shown to be in reasonable agreement with the HERA data [1, 2, 3].

We discussed the models both in view of recent HERA data and in terms of their predictions for hard exclusive diffractive processes. For DIS, a distinguishing feature between the models is the behavior of the structure function of the gap events at small values of the momentum fraction ξ carried by the Pomeron or the gluon. There are indications that the data favors or faster increase at small ξ than expected for soft Pomeron exchange, and is more consistent with the behavior of the gluon structure function.

Analogously, the energy dependence of the exclusive process $\gamma p \to J/\psi\, p$ is governed by the probability that the Pomeron or gluon carries a small momentum fraction $\xi \simeq m_{J/\psi}^2/s$. The available data again favors the faster increase at small ξ given by gluon exchange.

The nuclear target A-dependence of hard exclusive processes is not consistent with a factorizable Pomeron, but can be understood on the basis of color transparency. Soft gluon interactions of compact $q\bar{q}$ pairs in the color field of the target should not to upset the predictions of color transparency.

The postulate [6, 7] that compact $q\bar{q}$ pairs can have soft interactions and change their color in the target will, if correct, have important consequences also for other processes where the color quantum numbers are essential. We discussed the case of quarkonium hadroproduction, where severe discrepancies have been found between QCD calculations and the data, which appear to be of leading twist in the quark mass. Soft color interactions in the target could help explain why states such as the J/ψ, ψ' and χ_1, which cannot be produced directly by the fusion of two gluons, do not have suppressed production cross sections and are produced unpolarized.

The HERA gap events have focused attention on our limited understanding of how soft color interactions transform the perturbative parton state into the observed hadron distributions. It will be interesting to study experimentally which conditions can be imposed on the hadron distributions in DIS without changing the x_{Bj} and Q^2 dependence of the structure function. The gap condition may be but one of many possibilities.

Acknowledgements

PH would like to thank W. Buchmüller and G. Ingelman for helpful discussions.

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