Diffractive Hard Scattering with a Coherent Pomeron

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Abstract

Diffractive scattering involves exchange of a Pomeron to make a rapidity gap. It is normally assumed that to get a hard scattering in diffraction, one may treat the Pomeron as an ordinary particle, which has distributions of gluons and quarks. We show that this is not so: When we use perturbative QCD, there is a breakdown of the factorization theorem. The whole Pomeron can initiate the hard scattering, even though it is not point-like. Qualitatively, but not quantitatively, this gives the same effect as a delta function term in the gluon density in a Pomeron.
1 Introduction

Diffractive scattering in a high energy hadron collision is a rather spectacular process. One of the initial hadrons emerges from the collision unscathed and only slightly deflected, and there is a large rapidity gap between the diffracted hadron and the other final-state particles. At collider energies, 10\% to 20\% of all interactions are diffractive \[ 1, 2 \]. Diffraction is due to Pomeron exchange, Fig. 1, but the exact nature of the Pomeron in QCD is not yet elucidated.

Now, consider diffractive hard scattering; this means that we consider diffractive final states that contain the products of a hard scattering. One example is the production of jets in diffractive hadron-hadron collisions, for which data has been reported \[ 3, 4 \] by the UA8 experiment. Also, a few years ago, UA1 reported a measurement \[ 5 \] of diffractive bottom quark production.

The conventional picture of hard scattering in diffractive processes, due to Ingelman and Schlein \[ 6 \], is to apply the usual hard-scattering formalism \[ 7 \] but to a Pomeron target. For example, one has deep-inelastic lepton-Pomeron scattering and jet production in Pomeron-hadron collisions. This leads to the concept of the distributions of quarks and gluons in a Pomeron. With a typical ansatz for these distributions, one gets cross sections of the correct order of magnitude \[ 3, 4 \].

Frankfurt and Strikman \[ 8 \] (see also Frankfurt \[ 9 \]) showed that there are leading twist contributions that do not correspond to the Ingelman-Schlein mechanism. These give what we will call coherent diffractive hard scattering, where almost all the longitudinal momentum of the Pomeron goes into the hard scattering. The latest UA8 results \[ 4 \] indicate that about 30\% of their observed diffractive 2 jet events are consistent with coherent hard diffraction.

In this paper we will elaborate the theory of coherent hard diffraction by explaining that the existence of leading twist coherent hard diffraction is associated with a breakdown of the QCD factorization theorem in diffractive processes. Coherent hard diffraction is not obtained from parton distributions in a Pomeron.

We will point out that one failure of the factorization theorem is that we do not expect the same effect to dominate in diffractive deep-inelastic leptonproduction. Thus one would not see universality of parton densities in the Pomeron when one tries to make a simultaneous fit of the Ingelman-Schlein formulae for diffractive deep inelastic lepton-hadron scattering and for jet production etc in diffractive scattering in hadron-hadron collisions.
In a recent interesting paper, Donnachie and Landshoff [10] have made a calculation of diffractive production of high $P_T$ jets in photon-proton collisions. They find that because of a final state interaction, they get events of a similar kind to our coherent hard diffraction. This is in a kinematic region where the photon is point-like, so that there is not a spectator jet for the photon. Our prediction is that their cross section is higher twist, in contrast to the leading twist nature of coherent hard diffraction in proton-proton collisions. The explicit formulae given by Donnachie and Landshoff are indeed higher twist, in agreement with our general argument. Thus their cross section compared with the Ingelman-Schlein process decreases as $1/P_T^2$ when $P_T$ is large. Our coherent Pomeron mechanism in hadron-hadron collisions is leading twist: it has no such suppression at large $P_T$.

2 Hard Scattering and Diffraction

2.1 Diffraction

In diffraction, Fig. 1, we define $t$ to be the invariant momentum transfer and $s'$ to be the mass squared of the final state excluding the diffracted proton. Then we let $\xi \equiv s'/s$, so that $1 - \xi$ is the fractional longitudinal momentum of the outgoing diffracted proton. We take $s$ to be large, $-t \ll s$, and $\xi \ll 1$. There will typically be a rapidity gap of about $\ln(1/\xi)$ between the diffracted proton and the rest of the final state. In the data from the UA8 experiment reported in [3, 4, 11], $\sqrt{s} = 630$ GeV, and $1 - \xi$ is between about 0.90 and 0.96, so that $\sqrt{s'}$ is between about 130 and 200 GeV.

The usual theory of diffraction uses Regge theory with a triple Pomeron coupling to give a cross section

$$s' \frac{d\sigma}{ds' dt} \simeq \left( \frac{s}{s'} \right)^{2(\alpha_P(t)-1)} \left( \frac{s'}{s_0} \right)^{\alpha_P(0)-1} \times \text{(function of } t\text{).}$$  \hspace{1cm} (1)

Here $\alpha_P(t)$ is the Regge trajectory of the vacuum pole. Collider data [2, 4, 14] (from the ISR, the SppS and the Tevatron) agrees with conventional expectations for this trajectory (e.g., $\alpha_P(0) \simeq 1.08$).

Because of the $t$ dependence of the Pomeron trajectory, a softening of the distribution over $\xi$ is predicted as $-t$ increases. This softening has been recently observed at Tevatron [4]. However, when perturbation theory applies,
presumably at large \(-t\), QCD predicts \(\alpha_p(t)\) is larger than 1. This is the first distinctive property of the perturbative Pomeron.

## 2.2 Hard Diffraction

Now let us require that there be a hard scattering in addition to the diffraction. For example, we might ask that there be a heavy quark, or a jet, or a Drell-Yan pair. Such processes we will call ‘hard diffraction’.

We define \(x_A\) and \(x_B\) to be the fractions of the initial hadrons’ longitudinal momenta that are carried into the hard scattering; these two variables are defined at the parton level for all processes with a hard scattering. Then we let \(\beta\) be the fraction of the Pomeron’s momentum that goes into the hard scattering; this satisfies \(\beta = x_B/\xi\). Since the variables \(x_A\), \(x_B\) and \(\beta\) are defined at the partonic level, their values cannot be readily extracted from an experimental event. However, it is possible to define from a 2 jet event, the minimum values of \(x_A\), \(x_B\) and \(\beta\) that are necessary to make the event from parton-parton scattering. When we discuss values for these variables as computed from an event, it will be these minimum values that we actually mean.

The model of Ingelman and Schlein is to use the usual factorization formula but to apply it to Pomeron-hadron scattering. This corresponds to saying that diagrams like Fig. 2 dominate, so that

\[
\sigma(A + \text{Pomeron} \rightarrow \text{Jets} + X) = \sum_{a,b} f_{a/A}(x_A)f_{b/P}(\beta)\hat{\sigma}(a + b \rightarrow \text{Jets}) + \text{higher orders in } \alpha_s. \tag{2}
\]

Here, \(\hat{\sigma}\) is the short-distance parton-level cross section for the hard scattering, which, for the sake of definiteness, we have assumed to be for jet production; it is the same as in totally inclusive hard scattering. The sums are over all parton species (gluon, quarks and antiquarks). The densities, \(f_{b/P}(\beta)\), of partons in a Pomeron, should be universal between different processes. For example, the same densities that are measured in diffractive proton-antiproton collisions can be used to predict diffractive deep inelastic scattering at HERA, if the Ingelman-Schlein model is correct.
2.3 Phenomenology

One can estimate the size of the cross section by using an ansatz for the distribution of partons in a Pomeron. The predictions are in at least order-of-magnitude agreement with experiment [3, 4, 5], when the distributions are normalized by the momentum sum rule (which is not necessarily valid [12] for the Pomeron).

Diffractive events will have the diffracted proton separated from the rest of the event by a rapidity gap. This remainder of the event, of mass $\sqrt{s'}$, is expected, in the Ingelman and Schlein picture, to look qualitatively like a normal hadron-hadron scattering with $s$ set equal to $s'$. (The detailed properties of multiple Pomeron interactions can change the quantitative properties of Pomeron-hadron final-states as compared with hadron-hadron final states.)

3 Coherent Hard Diffraction

The Ingelman-Schlein model contributes to the cross section, since the corresponding diagrams, Fig. 2, do exist. We will now show that there is another contribution where the whole Pomeron induces the hard scattering. This we term ‘coherent hard diffraction’. The mechanism is illustrated by the lowest order graphs, shown in Fig. 3.

There is an apparent similarity of Pomeron-hadron and photon-hadron scattering, since Fig. 1 can also describe electron-hadron scattering with exchange of a photon of low $q^2$. The similarity is only apparent, since we will see that coherent hard diffraction only occurs because of a breakdown of the factorization theorem, whereas that theorem remains true for photoproduction: The photon can be genuinely point-like, but the Pomeron is not.

3.1 Failure of Factorization Theorem for Coherent Hard Diffraction

3.1.1 Leading graphs

Let us consider the proof [1] of the factorization theorem when one requires the final state to be diffractive. To be definite, we will consider the hard process to be the production of jets of some transverse energy $E_T$. The definition of the cross section will be subject to some kinematic conditions,
the exact details of which will be irrelevant. We will consider graphs at the leading power of the relevant large or small variables \((E_T, s, \xi)\), and we will focus particularly on the region appropriate to coherent hard diffraction, i.e., where \(\beta \equiv x_B/\xi\) is close to unity.

The simplest graphs that give hard scattering have one gluon coming into the hard scattering from each hadron—Fig. 4. These have a standard parton model interpretation:

\[
\sigma(A + B \rightarrow \text{jets} + X) = f_{a/A}(x_A)f_{b/B}(x_B)\hat{\sigma},
\]

in terms of parton densities and a short distance cross section. The contribution of this graph is at the leading power of the momentum scale, \(E_T\), of the jet (for large \(E_T\)). There are power law corrections in \(E_T\) (‘higher twist’) to this result that are not covered by the factorization theorem.

To get the leading power of \(\xi\), for small \(\xi\), we need to exchange a line of the highest possible spin between the lower proton and the hard scattering, that is, we must have gluon exchange. Since the effective spins of both the Pomeron and the gluon are close to 1, the power law for \(\xi\) is approximately the same for gluon exchange as for diffraction caused by Pomeron exchange.

However Fig. 4 does not give a possible model for coherent hard diffraction, since the gluon is a color octet. To get a diffracted proton with a rapidity gap, we need color singlet exchange, which implies a minimum of a two-gluon exchange, Fig. 3.

Individual graphs like Fig. 3 certainly give leading power contributions. But they do not have a parton model interpretation, since they do not involve single gluon exchange. To get the usual factorization theorem, some kind of cancellation is required. These cancellations are part of the proof [7], in the case of a totally inclusive cross section, with no diffractive requirement on the final state. If these cancellations were to remain true with diffractive final states then coherent hard diffraction would be a higher-twist effect.

### 3.2 Soft Gluon Needed

We will now show that the cancellations fail in the diffractive case. Now, both of the lower gluons in Fig. 3 have transverse momenta much less than \(E_T\), the transverse energy of the jets. Let the longitudinal momentum fractions for the gluons be \(x'\) and \(\xi - x'\). There are two cases to consider: (i) Collinear
gluons: where both these momentum fractions are comparable. (ii) Soft gluon: where $x' \ll \xi$ or $\xi - x' \ll \xi$.

Now, by gauge invariance, the single gluon in Fig. 4 must be accompanied by a gluon field, and this is accomplished by higher order graphs such as Fig. 3, with both the lower gluons in the collinear region. A relatively simple Ward identity argument shows that multigluon exchanges in the collinear region sum up to give a correctly gauge-invariant gluon number density. That is, we effectively get an exchange of a single color octet gluon. This part of the argument depends on the fact that when the collinear gluons couple to an oppositely moving gluon, as they do at the hard scattering, then they form a highly virtual state. The virtuality is of order $E_T$. This part of the argument is unaltered by the requirement of a diffractive final state.

Soft gluons are another matter. Graph-by-graph in Fig. 3, we have a leading contribution where one of the exchanged gluons is soft, i.e., it has a very small longitudinal momentum fraction. In the graph, the line marked ‘L’ remains of low virtuality instead of being off shell by order $E_T$. This low virtuality line has a rapidity that is on the opposite side of the rapidity of the hard scattering to the diffracted proton.

Now, there is a very nontrivial cancellation of the effects of soft gluons in the inclusive cross section. The proof of the cancellation is quite complicated; it uses Ward identities, causality, and a unitarity sum over final states.

Part of the unitarity sum occurs where the lower end of a gluon attaches to the diffracted proton far in the future relative to the hard scattering. Some graphs involved in the cancellation are shown in Fig. 4. These graphs cannot all satisfy the diffractive condition. Indeed, some of these final-state interactions are relevant to filling in the rapidity gap between the beam jets and the rest of the event. This part of the argument was known before the days of QCD [13, 14], and it is used as part of the full QCD proof [7].

Some intuition can be gained from considering what happens in space-time. We have a collision of Lorentz contracted and time-dilated hadrons. At a particular point, jets are made by the collision over a small distance scale $1/Q$ of one gluon out of each hadron. The cross section is determined at the moment of the hard scattering, and interactions outside the past light cone of the hard scattering cannot affect the cross section.

But when we have hard diffractive scattering, the remnants of one of the initial hadrons must reassemble themselves into a single hadron again, and that requires final-state interactions over a long time scale.
Now the unitarity cancellation we need to get factorization for the inclusive hard-scattering cross section involves adding together collections of graphs such as those shown in Fig. 5, which differ by the placement of the final-state cut. Some of these graphs involve octet color exchange, and therefore do not contribute to diffraction. Non-factorization of the diffractive hard scattering cross section is thereby established. The non-factorization occurs at the lowest relevant order of perturbation theory. Since the lowest order non-factorizing term comes from Fig. 3, essentially all of the longitudinal momentum of the exchanged system goes into the hard scattering. Thus we have exactly the effect advertised above. There is an effectively coherent contribution of the Pomeron to hard diffraction.

So far, we have considered the lowest order diagrams in pQCD for hard diffraction. These diagrams give the coupling for the perturbative pomeron to the proton. But, particularly at smaller $\xi$, we must sum higher order graphs for the exchange. Common wisdom is that the sum of leading logarithms in $\ln \xi$ gives (in the light cone gauge) a gluon ladder for the exchange of a perturbative Pomeron. This ladder will not change the coupling of the Pomeron, but it will change the power-law dependence of the amplitude on $\xi$. Such corrections become very important when $\ln(0.1/\xi) > 1/\alpha_s$. Furthermore, extra exchanged gluons can also contribute without power suppression.

### 3.3 Power Laws

A distinctive consequence of our factorization-violating mechanism is the dependence of the cross section on the variable $\beta = x_B/\xi$. In the approximation that radiation of extra gluons is neglected, the diagrams of Fig. 3 correspond to a situation where the whole momentum of pomeron initiates the hard scattering. Thus there is a $\delta(\beta - 1)$ dependence on $\beta$. Radiation of quarks and gluons will smooth out this delta function.

A slightly different singular behavior, like $1/(1 - \beta)$, is obtained from diagrams where two gluons (quarks) are radiated from the same exchanged gluon line. In both cases, we have a distinctive sharp peak at $\beta = 1$. Such diagrams die out more rapidly with increasing $|t|$ than those of Fig. 3.

Moreover, a nontrivial change of the $\beta$ distribution is expected as $t$ varies. According to conventional wisdom, nonperturbative QCD physics dominates at small $t$. This is the region where models of the Pomeron as a bound state of quarks and gluons may be applicable. Then the Ingelman-Schlein mechanism
would be appropriate. We might expect the perturbative contribution to be relatively small. In particular, the coherent perturbative $\delta(\beta-1)$ contribution is likely to survive only for small size parton configurations in the diffracted hadron.

On the other hand, at larger $-t$, pQCD predicts suppression of the long-distance nonperturbative physics, as a result of the color screening phenomenon. The contribution of large interquark distances in the wave function of colliding protons for diffractive processes is suppressed, for the following reasons:

i The lack of gluon radiation—for a recent discussion see [13].

ii Inelastic diffraction is suppressed for the collisions of black bodies.

iii The singularity of the potential in realistic quark models of a hadron leads to the dominance of small interquark transverse distances in the diffractively scattered proton when the momentum transfer $t$ is large. Then the perturbative Pomeron should dominate, and coherent hard diffraction should become much more important. Thus when $-t$ is around several GeV$^2$, a peak at $\beta = 1$ should become prominent.

We conclude that the $\beta$-dependence of hard diffractive processes at $\beta$ near 1 is a measure of the perturbative Pomeron contribution at any $t$. To visualize the expected dramatic effects, let us parameterize the dependence of hard diffractive processes on $\beta$ by the form $(1-\beta)^N$. Typical models for soft physics give $N = 5$ (multiperipheral models), or $N = 1$ (Pomeron as bound system of gluons), etc. But the coherent pomeron contribution gives $N = -1$. The relative size of the $N = -1$ term gives a measure of the importance of perturbative Pomeron physics.

Another distinctive feature of the perturbative Pomeron is the dependence of the cross section for diffractive dissociation on $\xi$. Let us parameterize it as $1/\xi^n$. When $t$ is small, $n$ is less than 1 and decreases with $t$. But when $t$ is large and $M_X^2 \ll s$, we find that $n$ is larger than 1, according to current wisdom of pQCD [16].

In reality, fully asymptotic behavior for the perturbative Pomeron is only achieved at extremely large energies. So the effective value on $n$ at practical values of $s$ will depend on $s$. We expect that a reasonable description of hard diffractive processes at the CERN collider and the Tevatron, but possibly not
in the SSC-LHC energy range, corresponds to the exchange of two gluons and low-order radiative corrections to this exchange. (These radiative corrections will give a few rungs in the ladder for the full perturbative Pomeron.)

A further change in the fraction of the coherent contribution arises when \( x_A \) is not small. Now, the minimum value of \( x_A \) is \( 4E_T^2/s' \), with \( E_T \) being the transverse energy of one of the jets. There is a factor in the cross section of \( x_A G(x_A, 4E_T^2) \) or \( x_A q(x_A, 4E_T^2) \), depending on whether the Pomeron scatters off a gluon or a valence quark. Here \( G(x_A, Q^2) \) and \( q(x_A, Q^2) \) are the usual gluon and quark distributions in a nucleon. At small \( x_A \), scattering off gluons dominates, but at large \( x_A \), scattering of quarks dominates. The coupling of the perturbative Pomeron to a quark is lower than its coupling to a gluon, and the relative fraction of the coherent \( \delta(x_B/\xi - 1) \) term to the Ingelman-Schlein continuum term will depend on the color charge of the parton coming from the non-diffracted hadron.

4 Conclusions

We have seen that there should be a coherent component of hard diffraction in hadron-hadron collisions. That is, the whole Pomeron can induce the hard scattering. The result is that the products of the hard scattering (jets, or heavy quarks, for example) will appear relatively close to the edge of the diffractive rapidity gap. Evidence for a substantial coherent term in diffractive jet production has recently been reported by the UA8 experiment [4]. Further calculational work is needed to establish whether the theoretical predictions are in quantitative agreement with experiment.

The coherent contribution should be present in addition to the contribution discussed by Ingelman and Schlein [6]. However, we should not expect factorization to be exactly valid for the Ingelman-Schlein contribution.

At first sight, the coherent term behaves like a \( \delta(1 - \beta) \) component for the gluon distribution in a Pomeron. (Compare the experimental results from UA8 [4].) There will also be a singular \( 1/(1 - \beta) \) contribution [8]; this singular component will give similar experimental consequences to the delta-function contribution, after smearing by gluon radiation, by hadronization and by calorimeter resolution.

But the rules of calculation are not those of standard hard scattering, because of the need for a soft gluon. This will imply that we should expect
violations of the universality of the parton densities.

In particular, we should not expect the coherent Pomeron to manifest itself in diffractive deep inelastic lepton scattering, as at HERA. The reason is that the soft gluon in Fig. 3 will no longer have an opposite-side colored object to couple to. We are talking here about the kinematic region where $\xi$, the fractional momentum of the Pomeron, is not much larger than $x_{Bj}$. But coherent hard diffraction can be leading twist in the process $\gamma^*(Q^2) + \text{Pomeron} \to \text{jets}(E_T) + X$ when

$$Q^2 \ll E_T^2 \ll s_{\gamma^*+\text{Pomeron}}.$$  

The higher twist result of Donnachie and Landshoff [10] applies when $E_T^2$ is of order $s_{\gamma^*+\text{Pomeron}}$.

Another manifestation of the breakdown of factorization may be that the ratio of coherent hard diffraction to Ingelman-Schlein hard diffraction will vary in hadron-hadron collisions. Quark-initiated processes will have less of a coherent fraction than gluon-initiated processes, because of the smaller color charge of the quarks. A comparison of the Drell-Yan process with jet production, and of the cross section at small $x_A$ and large $x_A$ would therefore be rather illuminating.

Since we need separated color for our mechanism to provide an effective contribution, we expect that Sudakov effects can suppress it, just as in the Landshoff mechanism for elastic hadron-hadron scattering. This is surely the case for the contribution of configurations with large transverse distances between quarks [13]. But if we go to large momentum transfer $-t$, then the transverse distances involved should get smaller, where the Sudakov suppression should be much reduced. Note also that the perturbative approximation to the Pomeron should be much better than at low $t$. The UA8 measurements have moderate values of $|t|$—roughly between 1 and 2 GeV$^2$.

More work is obviously needed on quantitative estimates of the cross section.

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Figure Captions

Fig. 1 Diffractive scattering by Pomeron exchange.

Fig. 2 Ingelman-Schlein model for hard diffractive scattering.

Fig. 3 Typical lowest order graph for coherent hard diffraction.

Fig. 4 Lowest order graphs for hard scattering.

Fig. 5 Unitarity cancellation in hard scattering includes both of these graphs.