ANL-HEP-CP-96-74
October 20, 1996
CONF-9706210--

THE HARD GLUON COMPONENT OF THE QCD POMERON

Alan R. White*
High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439.

Abstract

We argue that deep-inelastic diffractive scaling provides fundamental insight into the QCD Pomeron. The logarithmic scaling violations seen experimentally are in conflict with the scale-invariance of the BFKL Pomeron and with phenomenological two-gluon models. Instead the Pomeron appears as a single gluon at short-distances, indicating the appearance of a Super-Critical phase of Reggeon Field Theory. That the color compensation takes place at a longer distance is consistent with the Pomeron carrying odd color charge parity.

Invited talk presented at the Workshop on Quantum Chromodynamics: Collisions, Confinement and Chaos, American University of Paris, France, June 3-8, 1996

* Work supported by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38

DISCLAIMER

1. INTRODUCTION

Deep-inelastic scaling provided the original stimulation for the development of the parton model. Since the concept of a high-energy, short-distance, probe of a hadron is straightforward in the deep-inelastic process, it also has the most rigorous foundation for the application of parton model ideas within QCD. The observed scaling violations provide much of the information on partonic structure that is the basis for the successful application of perturbative QCD to a wide range of hadronic physics.

The observation of diffractive deep-inelastic scaling at HERA has opened up a new realm of strong interaction physics. The Pomeron, which in QCD is deeply tied to all of the long distance confinement dynamics, can now be studied in detail at short distances. We can anticipate that diffractive scaling violations will give crucial information on the structure of this dynamically central part of QCD. Indeed, as we shall suggest in this talk, major insight into the formulation of the parton model within QCD may actually result. The outline of the talk is as follows.

We begin with a short summary of standard perturbative factorization, DGLAP evolution, and the renormalization group. Moving on to small-x, we note that the scale-invariance of BFKL evolution implies it is not governed by the renormalization group. Nevertheless, it can consistently appear in a $k_\perp$-dependent gluon distribution and be combined with finite-order $\ln[Q^2]$ scaling violations in $F_2(x, Q^2)$.

In the diffractive cross-section $F_2^D(x, \beta, Q^2)$ there is, however, a direct conflict between the scale-invariance property of the BFKL Pomeron and the logarithmic scaling violations which, according to a recent H1 analysis[1], are present experimentally. As H1 show, their results require that, at short distances, the Pomeron behaves like a single gluon (rather than the perturbative two-gluon bound state that is the BFKL Pomeron[2]). Within QCD, gauge invariance makes this is a very difficult property to realize. To explain how it can be achieved it is necessary to discuss the solution we have proposed to the full dynamical problem of the Pomeron.

We first recall that at long distances the (soft) Pomeron can be identified phenomenologically as a Super-Critical Regge pole which couples to single quarks. We describe our arguments (first put forward[3] more than fifteen years ago) for identifying a Super-Critical phase of the Pomeron in QCD[4]. In first approximation the Pomeron is a "reggeized gluon", with a dynamical mass, in a "reggeon condensate" background. The condensate can be thought of as approximating a very soft gluon configuration accompanying the reggeized gluon. The reggeized gluon mass scale and the condensate scale can be distinct because they carry opposite color charge parity. The resulting Pomeron is then distinguished from (higher-order corrections to) the

BFKL Pomeron in that it carries odd color charge parity. Necessarily, hadrons are not eigenstates of color parity. This is due to the appearance, in an infinite momentum hadron, of a condensate (soft gluon) component with non-trivial color properties. The presence of this component is also directly related to chiral symmetry breaking and is an essential part of the "parton" description of an infinite momentum hadron.

Finally we describe why, if the Pomeron is in a Super-Critical phase at short distances, we expect logarithmic scaling violations in deep-inelastic diffractive scattering due to the dominance of a single hard gluon, just as described by H1[1]. The essential feature is the separation of the hard scale of the reggeized gluon from the soft scale of the opposite color parity "condensate" (which compensates for the gluon color).

2. FACTORIZATION AND DGLAP EVOLUTION

It is well-known that in deep-inelastic scattering the operator-product expansion gives the leading-twist "factorization"

$$F_2(x,Q^2) \;=\; \sum_i \; C_i\Big(x,\frac{Q^2}{\mu},\alpha_s(\mu^2)\Big) \;\otimes\; f_i\Big(x,\mu^2,\alpha_s(\mu^2)\Big) \;+\; .... \qquad (2.1)$$

where the parton densities $f_i\Big(x,\mu^2,\alpha_s(\mu^2)\Big)$ are matrix elements of light-cone operators. The scale μ can be used to separate "hard" from "soft" momenta. Application of the renormalization group to the μ-dependence of (2.1) then allows the large Q^2 dependence of the coefficient functions C_i to be determined perturbatively via asymptotic freedom.

The formal apparatus of the operator product expansion and the renormalization group is translated into simple perturbative diagrammatic analysis via

- operator product expansion $\leftrightarrow$ factorization of collinear singularities
- renormalization group $\leftrightarrow$ summation of logarithms via (DGLAP) evolution equations.

That the solution of the DGLAP evolution equations leads to specified x-dependence, as well as Q^2 dependence, in deep-inelastic scattering is most easily seen from the "double log" approximation in which the leading $\ln[\frac{1}{x}]$ contribution is kept for each $\log[Q^2]$. This gives

$$xg(x,Q^2) \;\sim\; exp\Big[\Big(\frac{N\alpha_s}{\pi} ln[\frac{Q^2}{Q_0^2}] ln[\frac{1}{x}]\Big)^{\frac{1}{2}}\Big] \qquad (2.2)$$

This approximation can be modified to comply with the renormalization group but to fit the small-x behavior seen in experiment, Q_0 has to be unphysically small[5]!

3. BFKL EVOLUTION AT SMALL-x

To consistently explain the small-x rise of $F_2(x, Q^2)$ within QCD perturbation theory we can sum the leading $\ln[\frac{1}{x}]$ contributions. We sum "reggeized gluon ladders" via the BFKL equation[2] as illustrated in Fig. 1. i.e.

$$F_2(x, Q^2) = \int_x^1 \frac{dx'}{x'} \int \frac{dQ_t^2}{Q_t^2} F_2^B(x', Q_t^2, Q^2) \otimes f(x/x', Q_t^2) \tag{3.1}$$

where $f(x, k^2)$ satisfies the "scale-invariant" BFKL equation

$$\frac{\partial}{\partial ln[\frac{1}{x}]} f(x, k^2) = f^0 + \frac{g^2}{8\pi^3} \int \frac{d^2k'}{k'^4} K(k', k) f(x, k') \tag{3.2}$$

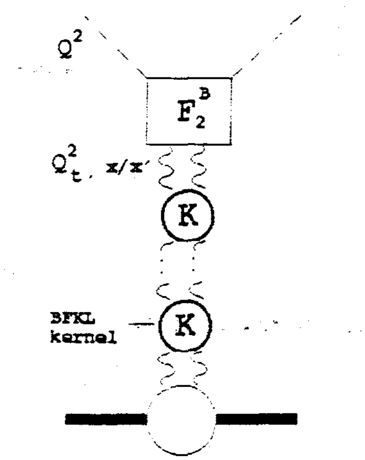

Fig. 1

and, as illustrated, $F_2^B(x', Q_t^2, Q^2)$ comes from the quark box.

Although the scale invariance of BFKL evolution implies it can not be derived via the renormalization group, equations (3.1) and (3.2) can be made consistent with DGLAP evolution by introducing non-perturbative splitting functions[6]. For our purposes, we can consistently assume the BFKL small-x evolution takes place with an infra-red transverse momentum cut-off. This (superficially at least) justifies neglect of the evolution of the coupling and allows the cut-off to provide the scale for the $\ln[Q^2]$ arising from the quark box diagram (since the cut-off will apply also to the Q_t integration in (3.1)). Phenomenologically this implies we can describe the Q^2 and x dependence (at small-x) by the "parton model" result

$$F_2(x, Q^2) \simeq \frac{\alpha_s}{3\pi} \sum_q e_q^2 x g(x) \left(\frac{2}{3} + \ln \frac{Q^2}{m_g^2} \right) . \tag{3.3}$$

where, the simple parameterization of the "gluon distribution" $g(x) = Ax^{-1-c}$ represents BFKL evolution and the "gluon mass" $m_g \sim 1$ GeV is the infra-red cut-off providing the scale for the logarithm coming from the quark box. The simple parametrization (3.3) fits the data very well.

4. DEEP-INELASTIC DIFFRACTION

To study deep-inelastic diffractive scaling we consider the diffractive structure function $F^D(x_{\mathbb{P}}, \beta, Q^2)$ which is the large rapidity gap component of F_2. In the notation of Fig. 2 we define

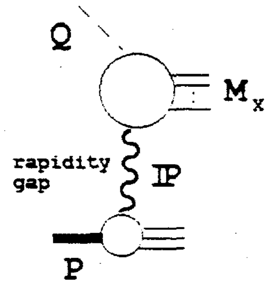

Fig. 2

$$W^2 = (P+Q)^2, \ \beta = \frac{Q^2}{Q^2+M_X^2}, \ x_{\mathbb{P}} = \frac{Q^2+M_X^2}{Q^2+W^2} \quad (4.1)$$

Diffraction is a small-$x_{\mathbb{P}}$ phenomenon and gluon exchanges give the leading perturbative behavior. The lowest-order (or BFKL Pomeron) contribution is (color zero) two-gluon exchange coupling via a quark-antiquark pair as in Fig. 3.

Now the scale-invariance of the BFKL Pomeron (or, equivalently, the infra-red finiteness due to gauge invariance) causes a problem. Consider the $k_\perp$ integration indicated in the diagrams of Fig. 3. For $k_\perp^2 \sim Q^2 >> t$ we obtain

$$\int \frac{d^2k_\perp}{k_\perp^4} \sim \frac{1}{Q^2} \quad (4.2)$$

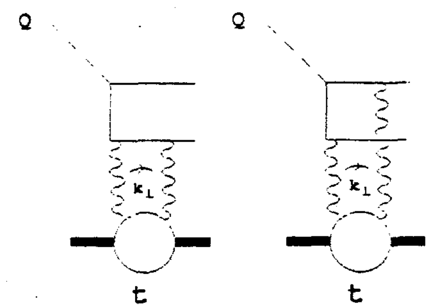

Fig. 3

giving non-leading twist $(1/Q^4)$ behavior for the total cross-section. Consequently the leading-twist behavior has to come from the small $k_\perp$ region of the diagrams. At first sight we can treat this region with a gluon mass infra-red cut-off, as we did for the total cross-section. However, a manifestation of the infra-red finiteness of the BFKL Pomeron is that the cut-off dependence cancels between the two diagrams shown. Since no scale remains, the $\ln[Q^2]$ produced by the quark loop must simultaneously cancel - as indeed it does[7]. The same cancellation occurs in any model which represents the Pomeron as a color zero combination of two "non-perturbative" gluon propagators.

To reproduce the $\ln[Q^2]$ dependence seen in the H1 data[1], it is necessary for one of the gluons in Fig. 3 to be present, with an effective infra-red cut-off, but with the color exchange compensated by some interaction (perturbative or non-perturbative) associated with a smaller $k_\perp$ scale. This would allow the non-cancellation of the gluon infra-red cut-off. We would like to say the single "hard" gluon is accompanied by a cloud of "soft" gluons which cancels the color exchanged, but not the cut-off dependence. However, it is gauge invariance which produces the cut-off cancellation in the BFKL Pomeron and this should generalise to the exchange of any number of gluons. Gauge invariance implies all gluons in a color zero multiple gluon exchange are identical. This argument could be avoided only if the soft gluon cloud carries some quantum number distinguishing it from single gluon exchange - as we describe in the next Section.

5. THE SUPER-CRITICAL POMERON IN QCD

Phenomenologically, the soft Pomeron is well-described as a Super-Critical Regge pole, i.e. $\alpha_{\mathbb{P}}(0) \equiv \alpha^0 > 1$. Within Reggeon Field Theory (RFT) it is known how this violation of unitarity is corrected by the summation of higher-order diagrams. Resummation gives[4] the renormalized intercept $\alpha^R_{\mathbb{P}}(0) < 1$ together with a "Pomeron condensate". The condensate generates new classes of RFT diagrams whose physical interpretation is, at first, not apparent. For example, diagrams such as that of Fig. 4 appear. The transverse momentum poles produced by the zero energy two-Pomeron propagators can[4], in fact, be interpreted as particle poles, allowing the identification of the diagram as a (Pomeron) transition into two odd-signature reggeons, or "reggeized gluons" (with no color!) In this way divergences in rapidity produced by $\alpha^0 > 1$ are converted to divergences in transverse momentum associated with vector particles. Consequently the Super-Critical phase can be characterized by the "deconfinement of a vector gluon" on the Pomeron trajectory. It is very interesting to consider how this RFT phase might be realized in QCD.

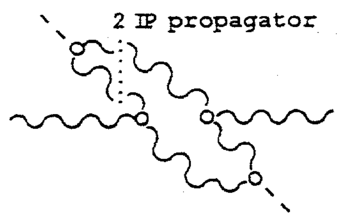

Fig. 4

Since the RFT Critical bare intercept $\alpha^0_c > 1$, it is possible that $\alpha^0_c > \alpha^0 > 1$ is the present experimental situation. In this case the Sub-Critical expansion with $\alpha^0 > 1$, and no deconfined vector gluons present, would be the right description for the (long-distance) soft Pomeron. Nevertheless, if we are close to criticality, the Super-Critical phase, with a condensate and vector "gluons", could be present at short distances. This is how we will explain the H1 results, as we now elaborate.

It is not at all apparent that RFT is applicable to QCD since it requires an isolated Regge pole as a first approximation. The BFKL Pomeron is either a fixed branch-point or, with α_s running, is an infinite set of Regge poles. Higher-order perturbative calculations produce an even more complicated spectrum. It is hard to understand how a spectrum of this kind can be avoided, unless the QCD Pomeron is somehow distinguished from the BFKL Pomeron by, for example, a quantum number of the kind that is needed to expose the short-distance gluon seen by H1!

In field theory, bound-state Regge poles are never isolated. Only the Regge poles produced by reggeization (e.g. the reggeization of the gluon) are isolated. Our construction[4] of the Super-Critical Pomeron phase in QCD builds on the reggeization of the gluon. It begins by breaking the SU(3) gauge symmetry to SU(2) using the Higgs mechanism. In this case an SU(2) singlet ("deconfined") reggeized gluon is present in the physical spectrum. With massless quarks present there are (non-leading log) infra-red divergences present in the Regge limit of multiparticle quark/gluon scattering amplitudes which generate[4] a multi-gluon condensate related to the U(1) anomaly. These divergences produce a confinement spectrum for the reggeon states formed. As illustrated in Fig. 5, the (Super-Critical) Pomeron appears as the SU(2) singlet reggeized gluon in an "anomalous Odderon" condensate (i.e. a singlet combination of an odd number of gluons with even, rather than odd, SU(2) color charge parity and carrying zero transverse momentum).

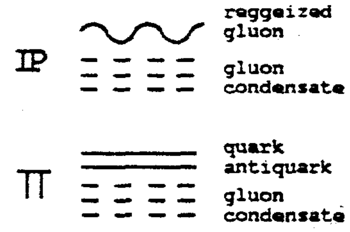

Fig. 5

The pion has a (Regge cut) odd signature constituent quark component, which the gluon condensate converts to a pseudoscalar even signature meson, and scattering takes place as illustrated in Fig. 6. There is a perturbative coupling of the reggeized gluon to the constituent quarks - as the additive quark model requires, and the condensate self-couples (via massless quark loops). Two crucial properties of the SU(2) construction are that it produces a Pomeron Regge pole described by RFT and that the breaking of chiral symmetry clearly accompanies confinement.

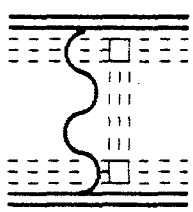
Fig. 6

To restore the gauge symmetry to SU(3) the Higgs sector must be decoupled. (In general this requires a $k_\perp$ cut-off.) In this process the condensate disappears and the gluons involved aquire a $k_\perp$ scale. If this (cut-off dependent) scale becomes identical to that of the reggeized gluon, the Pomeron effectively becomes a non-local object in terms of gluons. However, it carries a crucial remnant of the construction i.e. odd SU(3) color charge parity. The odd and even color parity, of the reggeized gluon and the condensate respectively, combine to give overall odd color parity. The SU(2) singlet condensate and quark/antiquark state have projections on both SU(3) singlet and octet states and so, in the SU(3) limit, the pion becomes a mixture of states with even and odd color parity (but odd physical parity). The quark-antiquark pair appear respectively in a color singlet or a color octet combination. The odd color parity Pomeron scatters the odd(even) state into the even(odd) state.

The construction we have outlined shows that in the Regge limit (below some $k_\perp$ cut-off) QCD is describable by RFT. The BFKL Pomeron does not contribute. (We have discussed elsewhere[4] why the Pomeron should be Critical if the cut-off is to be removable. We have also discussed the relevant constraint on the quark content of the theory.) A-priori the full theory may be above, or below, the critical point. As illustrated in Fig. 7, deep-inelastic diffractive scattering will expose the simplest perturbative contribution to the Pomeron. Odd color charge parity determines this to be four gluon exchange in which a single antisymmetric (color) octet gluon combines with a symmetric octet combination of three gluons. That the Pomeron is "in the Super-Critical phase" at the deep-inelastic scale implies that the symmetric octet forms a "condensate" i.e. has a lower $< k_\perp >$ scale than the single gluon. As discussed in the last Section, this will produce the hard gluon structure seen by H1[1].

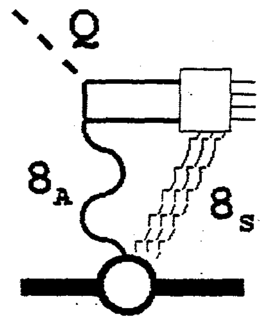

Fig. 7

References

[1] H1 Collaboration - pa02-61 ICHEP'96, Warsaw, Poland (1996).

[2] V. S. Fadin, E. A. Kuraev, L. N. Lipatov, *Sov. Phys. JETP* **45**, 199 (1977) ; Ya. Ya. Balitsky and L. N. Lipatov, *Sov. J. Nucl. Phys.* **28**, 822 (1978).

[3] A. R. White, Proceedings of the XVIth Rencontre de Moriond, Vol. 2 (1981).

[4] A. R. White, *Int. J. Mod. Phys.* **A6**, 1859 (1991), **A8**, 4755 (1993). (The construction of the second paper is currently being reformulated.)

[5] R. D. Ball and S. Forte, *Phys. Lett.* **B335**, 77 (1994).

[6] S. Catani, M. Ciafaloni and F. Hautmann, *Nucl. Phys.* **B366**, 135 (1991).

[7] J. Bartels and M. Wüsthoff, *Z. Phys.* **C66**, 157 (1995).