SLAC-PUB-6099
April 1993
(T/E)

# Observation of High Energy Quark-Antiquark Elastic Scattering with Mesonic Exchange[1]

Wai-Keung Tang

Stanford Linear Accelerator Center

Stanford University, Stanford, CA 94309

## Abstract

We studied the high energy quark anti-quark elastic scattering with an exchange of a mesonic state in the $t$ channel with $-t/\Lambda^2_{QCD} \gg 1$. Two methods are proposed to eliminate the strong background from bare pomeron, reggized gluon and odderon exchange. The feasibility of measuring mesonic reggeon exchange is discussed.

(Submitted to *Physics Letters* **B**)

---

[1]Work supported in part by Department of Energy contract DE-AC03-76SF00515.

## Introduction

With the advances of Tevatron, LHC and SSC, it is possible to study experimentally the Regge behavior in the parton level where the momentum transfer squared $-t \gg \Lambda^2_{QCD}$ but is still smaller than the center of mass energy squared $\hat{s}$ of the partons. The presence of a "large" scale $-t$ justifies the use of perturbative QCD. The dominant process is an exchange of a Balitsky-Fadin-Kuraev-Lipatov (BFKL) pomeron [1,4] between partons. Several hard partonic processes to measure the behavior of the BFKL pomeron [5-10] have been discussed in the literature. In Ref [10], A.H. Mueller and the author propose a process of high energy, fixed $t$ parton-parton elastic scattering through the exchange of a BFKL pomeron. The elastic scattering produces a final state which, at the parton level, contains two jets with a rapidity gap i.e. a region of rapidity in which no gluons are found. It is natural to extend this idea to the process whereby a mesonic reggeon is exchanged [12]. Even though the mesonic exchange process is suppressed by a factor of $\hat{s}^2$ with respect to pomeron exchange, the reggeon trajectory is itself interesting and it opens another window to test PQCD in double logarithmic approximation.

The energy dependence of the scattering cross section by exchanging a mesonic reggeon is $\hat{s}^{-2+2\omega_R}$ where $\omega_R$, $\sim 0.2$, in the interesting physical region [12], is the trajectory of the mesonic reggeon. The smalless of the trajectory and the suppression factor $-2$ in the energy dependence impose a serious obstacle to observing mesonic reggeon behavior. Thus, the rapidity between the two partons cannot be taken to be too large, otherwise the cross section will be too small to be observed.

At the parton level, there are several potential backgrounds to the signal of observing the interesting rapidity gap phenomena by exchanging a mesonic reggeon. The dominant one is the BFKL pomeron exchange, as mentioned above. Reggized gluon exchange also contributes if we assume that we cannot detect partons with transverse momentum smaller than a fixed parameter $\mu$. It can be of the same order as pomeron exchange if rapidity is not too large [14]. Thus, background from reggized gluon can be substantial. Even though quantitative prediction for the exchange of perturbative odderon is still lacking, we expect that it will not be too small, and may be comparable with that of mesonic reggeon exchange [16]. Thus, two methods to eliminate the strong background due to the exchange of pomeron, reggized gluon and odderon are suggested below.

The simplest way to eliminate all these background is to do $A\bar{B}$ and $AB$ collisions with two jets, tagged to be $q_i\bar{q}_i$ pairs, but with $q_i\bar{q}_i$ not the constituent quarks of hadrons $A$, $B$, and $\bar{B}$, e.g. $s\bar{s}$, $c\bar{c}$, and $d\bar{d}$ in $P\bar{P}$ and $PP$ collisions. Obviously, pomeron and reggized gluon contribution are subtracted out if we take the difference of the cross sections. The elimination of the background due to odderon through the tagging of apppropiate $q_i\bar{q}_i$ pairs needs some explanation. In general, the amplitudes of scattering of $q_iq_j$ and $q_i\bar{q}_j$ through the exchange of an odderon have a phase difference $\pi/2$. If we consider the difference the cross sections of two jets of $A\bar{B}$ and $AB$ collisions, odderon contribution cannot be eliminated. Instead, cross sections of $q_{i/A}\ \bar{q}_{j/\bar{B}} \rightarrow q_i\bar{q}_j$ and $q_{i/A}\ q_{j/B} \rightarrow q_iq_j$ scattering, where $q_{i/A}$ stands for quark $q_i$ from hadron $A$, add due to the $\pi/2$ phase difference in their amplitudes. However, the tagging of the final jets, taking $P\bar{P}$ and $PP$ collisions as an example, being $s\bar{s}$, $c\bar{c}$, $d\bar{d}$, eliminates odderon contributions completely, since there is complete cancellation between the scattering of $q_{i/P}\ \bar{q}_{i/\bar{P}} \rightarrow q_i\bar{q}_i$ and $q_{i/P}\ \bar{q}_{i/P} \rightarrow q_i\bar{q}_i$ if one assumes parton distribution of $\bar{q}_{i/\bar{P}}$ and $\bar{q}_{i/P}$ are the same for $\bar{q}_i = \bar{s},\ \bar{c},\ \bar{d}$.

The tagging of quarks in the extremely forward direction may have a serious efficiency problem, so we also suggest another method which exploits the fact that mesonic reggeon and pomeron (reggized gluon and odderon) couple differently to quark (anti-quarks) with different helicity states. A mesonic reggeon only couples to an initial quark anti-quark pair when they have opposite helicities. Pomeron, reggized gluon and odderon are insensitive to the helicities of quark and anti-quark. Thus, the difference of the cross sections of $A_\uparrow B_\uparrow$ and $A_\uparrow B_\downarrow$ collisions eliminates the contribution from pomeron, reggized gluon and odderon completely and only indicates the behavior of mesonic exchange. Chosing $B$ to be the anti-particle of $A$ would maximize the cross section since parton distribution of $\bar{q}_i$ in $B = \bar{A}$ is of the same order as parton distribution of $q_i$ in $A$. However, luminousity of an $A\bar{A}$ machine is limited due to the difficulty of producing a large number of anti-particles. It is not yet clear what is the best way to observe mesonic exchange phenomena.

Unfortunately, the above two methods also eliminate the contribution due to the quark quark backward scattering with mesonic exchange. It is obvious that cross section of quark quark scattering cancel completely once the difference of the cross sections of $P\bar{P}$ and $PP$ collision is taken. As mesonic reggeon can couple to an initial quark quark pair with any helicity states, quark quark backward scattering cannot contribute in the second method. Only the quark antiquark elastic scattering with mesonic reggeon exchange survives.

At the hadron level, the spectator interactions radiate soft gluons, producing hadrons across the rapidity interval and thus spoiling the rapidity gap. This soft gluon radiation is essential to prove the QCD factorization theorem, which relates parton to hadron cross section [13]. Thus, we have two options [14]: (*i*) we require that the soft gluon radiation is suppressed and estimates the rapidity-gap survival probability [15]: (*ii*) we allow the presence of soft gluons with transverse momentum $\mu \gg \Lambda_{QCD}$ [10]. Then QCD factorization holds, and one can use it to relate parton to hadron cross sections. In Ref. [14], this process is named quasi elastic scattering. In this paper we take the second approach.

**Quark Anti-quark Elastic Scattering**

We study the quark anti-quark scattering amplitudes with mesonic exchange in the $t$ channel. In the kinematic region,

$$\hat{s} \simeq \mid \hat{u} \mid \gg -t \gg \Lambda^2_{QCD}, \tag{1}$$

higher order corrections like $\sim \alpha_s[(\alpha_s/\pi)y^2]^n$ are important, when $y$, the rapidity between a quark and an anti-quark, defined by $y = \ln(\hat{s}/-t)$, is large. The strong coupling constant $\alpha_s$ is evaluated at $-t$. This is the double logarithmic (DL) approximation. The method of separating the softest virtual particle [17] allows one to calculate the partial wave amplitudes in the double logarithmic approximation [11]. The spinor structure of the Born term is preserved in higher order, so the scattering amplitudes of $q_i\bar{q}_i \rightarrow q_j\bar{q}_j$ through color singlet (the color octet is suppressed so we will not consider it) mesonic exchange can be written as [11]

$$A^p(\hat{s}, t) = \frac{\gamma_\mu^\perp \otimes \gamma_\mu^\perp}{\hat{s}} \frac{1}{N_c} \delta_{aa'}\delta_{bb'} M^p(y), \tag{2}$$

where $a, b$ and $a', b'$ label the color states of the initial and final quarks and anti-quarks. The signature corresponding to even (odd) parts of the amplitude under the transformation $\hat{s} \leftrightarrow \hat{u} \simeq -\hat{s}$ is $p = 1 \;\; (-1)$. $M^p(y)$ gives all order corrections. Partial wave amplitude is evaluated by R. Kirschner and L.N. Lipatov [11], and the expression of the ampltiude can be obtained by performing a Mellin transformation [12]. As shown in Ref.[12], the difference between the magnitude of positive and negative signature singlet amplitudes with fixed strong coupling can be practically neglected up to SSC energies. They only have a phase difference of $\pi/2$. However, fixed coupling is not a good approximation, as the transverse momentum in the loop extends over the large range from $-t$ to $\hat{s}$. It is expected that the running coupling effect changes the amplitude greatly. We observed that behavior. The nature of the partial wave singularity changes from a square root branch cut to infinitely many poles [18]. However, inclusion of running coupling decreases the difference between positive and negative signature singlet amplitudes for the following reasons: the only difference between the positive and negative channels stems from the contribution of the double logarithmic soft gluon; the soft gluon contributes to the negative signature singlet channel but not the positive signature singlet channel [11]. The inclusion of the running coupling will decrease the importance of the soft gluon contribution, as the coupling between quark and gluon is smaller than in the fixed coupling case. Therefore, for practical purposes, we can take positive and negative singlet amplitudes to be equal in magnitude but with phase difference $\pi/2$. The positive signature amplitude with running coupling constant is [12]

$$M^{+}_{run}(y) \quad = \quad 0.895 \times 64\pi^3 b\,\omega_R^2 (\frac{\alpha_s}{2\pi a_0})^{1/2} e^{\omega_R y}, \tag{3}$$

with

$$a_0 = \frac{N_c^2 - 1}{2N_c}; \quad b = \frac{1}{16\pi^2}(\frac{11}{3}N_c - \frac{2}{3}N_f), \tag{4}$$

where $N_c$ ($N_f$) is the number of colors (flavors) and $\omega_R(\alpha_s)$ is the leading trajectory of the mesonic reggeon. It is a non-linear function of $\alpha_s(-t)$. Let $\omega_{max} = a_0/(8\pi^2 b)$

and the leading mesonic trajectory can be written as

$$\omega_R(\alpha_s) \quad = \quad \frac{\omega_{max}}{\rho_1 + \rho_2 \alpha_s^{-1/2}} \tag{5}$$

with

$$\rho_1 = 1.14 \times \frac{3}{4} \qquad\qquad \rho_2 = 0.90 \times \frac{2}{\pi}(\frac{\omega_{max}}{4\pi b})^{1/2}. \tag{6}$$

The numerical factors 0.895 in the normalization and 1.14 and 0.90 in the trajectory are the result of numerical fitting. The trajectory is of the order 0.2 in the interesting physical range. It's smallness imposes serious difficulty in observing the mesonic reggeon trajectory in the parton level experimentally. Sandwiching $A^p$ between appropiate spinors and averaging (summing) over initial (final) color states, we have, when the quark and anti-quark have opposite helicities,

$$|A^+_{run}(y)|^2 = \frac{4}{N_c^2}|M^+_{run}(y)|^2. \tag{7}$$

Here, we assume that the mass of quarks can be neglected when compared with the parton-parton center of mass energy $\sqrt{\hat{s}}$. Therefore, the differential cross section of $q_i\bar{q}_i \longrightarrow q_j\bar{q}_j$ is

$$\begin{aligned} \frac{d\hat{\sigma}_{\alpha\beta}}{dt} &= \frac{1}{16\pi\hat{s}^2}|A^+ + A^-|^2\delta_{\alpha,-\beta} \\ &\simeq \frac{1}{2\pi N_c^2\hat{s}^2}|M^+_{run}|^2\delta_{\alpha,-\beta} \end{aligned} \tag{8}$$

where $A^- \simeq iA^+$ and $\alpha(\beta)$ is the helicity of the initial quark (anti-quark).

**Observation of Mesonic Reggeon Exchange**

From Ref. [10], the most straightforward way to observe the mesonic scattering in the parton level is to look at the cross section of two jets, $x_A x_B d\sigma/dx_A dx_B dt$ where $x_A$ and $x_B$ are the longitudinal momenta fractions with respect to their parent hadrons. The two tagging jets must have nearly balancing transverse momenta and that no additional jets, above a transvese momentum scale $\mu$, be found in the rapidity interval between the tagging jets. Then, cross section due to quark anti-quark elastic scattering with mesonic reggeon exchange is

$$\begin{aligned} & x_A x_B \frac{d\sigma}{dx_A dx_B dt}(A_\lambda B_{\lambda'} \to j(x_A) j(x_B)) \\ = \;& N \sum_f \Big[\, x_A x_B \, Q^{\alpha/\lambda}_{f/A}(x_A)\, \bar{Q}^{\beta/\lambda'}_{f/B}(x_B) + (Q \leftrightarrow \bar{Q}) \,\Big] \frac{d\hat{\sigma}_{\alpha\beta}}{dt} \end{aligned} \tag{9}$$

where $Q^{\alpha/\lambda}_{f/A}$ ($\bar{Q}^{\alpha/\lambda}_{f/A}$) is the quark (anti-quark) distribution with helicity $\alpha$ in hadron $A$ with polarization $\lambda$. $N$ is the number of flavors of quark anti-quark pairs allowed in the final jets. For $P\bar{P}$ and $PP$ collisions $N = 3$, and the final quark anti-quark pair should be $s\bar{s}$, $c\bar{c}$, $d\bar{d}$ so that background from pomeron, reggized gluon and odderon can be eliminated. The differential cross section for this process is

$$\begin{aligned} & x_A x_B t \left[ \frac{d\sigma(P\bar{P})}{dx_A dx_B dt} - \frac{d\sigma(PP)}{dx_A dx_B dt} \right] \\ = \;& \frac{N}{2} \sum_f \Big[\, x_A x_B \, Q_{f/P}(x_A)\, \Delta\bar{Q}_{f/P}(x_B) + (Q \leftrightarrow \bar{Q}) \,\Big]\, t \frac{d\hat{\sigma}}{dt} \end{aligned} \tag{10}$$

with

$$\Delta Q_{f/P} = Q_{f/\bar{P}} - Q_{f/P}$$

$$\Delta\bar{Q}_{f/P} \;=\; \bar{Q}_{f/\bar{P}} - \bar{Q}_{f/P} \tag{11}$$

The hard scattering cross section $d\hat{\sigma}/dt$ is the usual one defined by Eq.8 without the delta function $\delta_{\alpha,-\beta}$. We are also interested in the difference of $d\sigma(A_\uparrow B_\uparrow)$ and $d\sigma(A_\uparrow B_\downarrow)$. In this case, $N = 5$ and one can write,

$$\begin{aligned} & x_A x_B t \left[ \frac{d\sigma(A_\uparrow B_\downarrow)}{dx_A dx_B dt} - \frac{d\sigma(A_\uparrow B_\uparrow)}{dx_A dx_B dt} \right] \\ = \;& N \sum_f \Big[\, x_A x_B\, \delta Q_{f/A}(x_A)\, \delta\bar{Q}_{f/B}(x_B) + (Q \leftrightarrow \bar{Q}) \,\Big]\, t \frac{d\hat{\sigma}}{dt} \end{aligned} \tag{12}$$

with

$$\begin{aligned} \delta Q_{f/A} &= Q^{\uparrow}_{f/A} - Q^{\downarrow}_{f/A} \\ \delta\bar{Q}_{f/A} &= \bar{Q}^{\uparrow}_{f/A} - \bar{Q}^{\downarrow}_{f/A} \end{aligned} \tag{13}$$

where $\uparrow$ ($\downarrow$) in the superscript of $Q$ means the helicity of the quark is parallel (anti-parallel) to that of the parent hadron.

The hard scattering cross section has a suppression factor $\hat{s}^{-2}$ so we want to minimize $\hat{s}$ with a reasonably large rapidity gap. Taking $y = 4$ and $-t = 25\text{GeV}^2$; $\hat{s} \simeq 1365\text{GeV}^2$, $\alpha_s = 0.223$, $\omega_R = 0.189$ and $td\hat{\sigma}/dt \sim 120$pb, if $x_A = x_B = 0.1$, the difference of the cross sections of $P\bar{P}$ and $PP$ collisions written in Eq.10 is $\sim 90$pb which is not too small and can be measured. If we take $A = P$ and $B = \bar{P}$, Eq.12 should give us the same order of magnitude but with the advantage of not tagging the final jets. In sum, the observation of mesonic reggeon exchange is possible, and it will be very interesting to measure the trajectroy of the mesonic reggeon.

**Acknowledgements**

I am very much indebted to A.H.Mueller for suggesting this work and for many stimulating discussions. Also thanks to Stanley Brodsky for continous encouragement and discussions.

# References


[1] E.A. Kuraev, L.N. lipatov and V.S. Fadin, Sov. Phys. JETP 45 (1977) 199.

[2] Ya.Ya. Balistsky and L.N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 822.

[3] L.N. Lipatov, Sov. Phys. JETP 63 (1986) 904.

[4] L.N. Lipatov, in: Pertubative QCD, ed. A.H. Mueller (World Scientific, Singapore, 1989).

[5] A.H. Mueller and H. Navelet, Nucl. Phys. B282 (1987) 727

[6] W.-K. Tang, Phys. Lett. B278 (1992) 363.

[7] J. Kwiecinski, A.D. Martin and P.J. Sutton, Phys. Lett. B287 (1992) 254 and Phys. Rev. D46 (1992) 921.

[8] J. Bartels, A. De Roeck and M. Loewe, Z. Phys. C54 (1992) 635.

[9] J. Bartels, M. Besancon, A. De Roeck and J. Kurzhoefer, DESY Preprint (1992).

[10] A.H. Mueller and W.-K. Tang, Phys. Lett. B284 (1992) 123.

[11] R. Kirschner and L.N. Lipatov, Sov. Phys. JETP 56 (1982) 266 and Nucl. Phys. B213 (1983) 122.

[12] W.-K. Tang, Columbia preprint, CU-TP-582 and SLAC preprint, SLAC-PUB-6024.

[13] J.C. Collins, D.E. Soper and G. Sterman in: Pertubative QCD, ed. A.H. Mueller (World Scientific, Singapore, 1989).

[14] V. Del Duca and W.-K. Tang, SLAC peprint, SLAC-PUB-6095 (1993).

[15] J.D. Bjorken, Phys. Rev. D47 (1992) 101.

[16] A.H. Mueller, private communication.

[17] R. Kirschner, Z. Phys. C31(1986) 135 and references therein.

[18] W.-K. Tang, in preparation.