Large-t, Triple-Pomeron Diffractive Processes in QCD

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(Received 25 August 1989)

In terms of perturbative QCD we calculate the basic features of high-mass (M_X) diffractive dissociation of hadrons at large momentum transfer t. We find that the distribution over $1-x=M_X^2/s$ should change from $1/(1-x)$ at small t to $(1-x)^{-1-2\omega_0}/\ln^3[1/(1-x)]$ at large t [where $\omega_0=\alpha_S(t)12\ln(2)/\pi$], and that the gluon distribution in the Pomeron should flatten with increasing $|t|$.

PACS numbers: 13.85.Ni, 12.38.Bx, 12.40.Gg

Investigation of hard high-energy processes has confirmed the basic predictions of perturbative QCD. One of the pressing questions now is to clarify the kinematical domain where the transition from soft physics (nonperturbative QCD) to hard physics (perturbative QCD) occurs for high-energy processes. We explain here that investigation of diffractive dissociation (all notations correspond to Fig. 1),

$$h+N\to p+X, \tag{1}$$

especially at large t, and also hard diffractive processes such as

$$h+N\to (\text{high-}p_t\text{ jet})+X+p \tag{2}$$

can help to resolve this problem. The interesting kinematics is

$$\begin{gathered} s=(k_h+k_N)^2\to\infty,\quad M_X^2/s=(k_h+k_N-k_p)^2/s\ll 1\,, \\ |(k_N-k_p)^2=t|\gg\mu^2,\quad |t|/s\ll 1,\quad |t|/M_X^2\ll 1\,, \end{gathered} \tag{3}$$

where $\mu\sim 1$ GeV is the scale of soft hadron processes.

At small t nonperturbative QCD—soft hadron physics (exchange by the Pomeron $\mathcal{P}$—by a ladder consisting of hadrons or quarks and gluons interacting with vacuum condensates) dominates in diffractive processes. In the case of large s and M_X^2 but $M_X^2/s\ll 1$, the conventional triple-Reggeon formula is expected to be valid (for a recent discussion and references see Ref. 1),

$$\frac{d\sigma}{dt\,dx}=\left(\frac{s}{M_X^2}\right)^{2\alpha_{\mathcal{P}}(t)-1}F_N^2(t)\eta_{\mathcal{PPP}}(t)(M_X^2)^{\Delta}. \tag{4}$$

Here $M_X^2=s(1-x)$ and x is the light-cone fraction of the initial nucleon momentum carried by the final proton p; $\alpha_{\mathcal{P}}(t)\simeq 1+\Delta+\alpha'_{\mathcal{P}}t$ is the trajectory of "bare soft Pomeron" whose intercept, obtained phenomenologically from fits to the energy dependence of the total hadron-hadron cross sections, is $\alpha_{\mathcal{P}}(0)-1\leq 0.1$; $F_N(t)$ is the form factor for the interaction of the Pomeron $\mathcal{P}$ with a nucleon. Up to numerical factors $\eta_{\mathcal{PPP}}(t)$ is the triple-Pomeron vertex. Accounting for the inelastic corrections to the diagram of Fig. 1 in the eikonal approximation leads to slowing down of the t dependence of the cross section, and to the additional factor in Eq. (4) which is a slow function of s,M_X^2.[1] Equation (4) is consistent with the current experimental data on diffractive processes (see Ref. 1 and references therein).

At sufficiently large t but $|t|/s\ll 1$, it is natural to expect that perturbative QCD should be applicable for the description of diffractive processes as a result of the decrease of the effective coupling constant $\alpha_S(t)$ with increasing $|t|$. The aim of this paper is to show that in the perturbative regime the cross sections of reactions (1) and (2) have several peculiar features which can be identified experimentally.

Since the gluon spin equals unity, at sufficiently large t in the approximation $\alpha_S(t)\ll 1$, $\alpha_S(t)\ln(s/M_X^2)\gg 1$, the diffractive processes in perturbative QCD are given in the light-cone gauge by the sum of ladder diagrams (Figs. 2 and 3) for reactions (1) and (2) with Reggeized two-gluon exchange in the t channel. This contribution is usually referred to in the literature as the perturbative Pomeron.[2]

The calculation of the large-t behavior of the residue

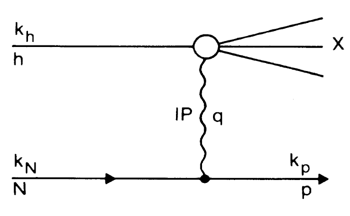

FIG. 1. Diagram for the process $h+N\to p+X$.

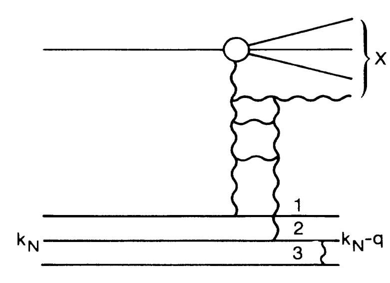

FIG. 2. Ladder diagram.

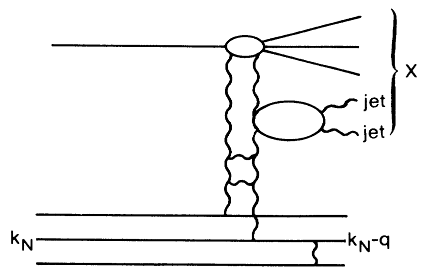

FIG. 3. Ladder diagram with jet production.

of the perturbative Pomeron which is described by the ladder diagrams of Figs. 2 and 3 in the kinematical region given by Eq. (3) leads to a comparatively slow decrease of the cross section with t:

$$\frac{d\sigma}{dt\,dM_X^2} \sim \frac{\alpha_S^6(t)}{|t|^5}\tilde{x}G_h(\tilde{x},-|t|)f^2\left(\frac{s}{M_X^2},|t|\right)\frac{M_X^2}{s^2}, \tag{5}$$

where $\tilde{x} \simeq |t|/M_X^2$ and $G_h(\tilde{x},|t|)$ is the gluon distribution in the hadron h at virtuality $|t|$. [We account for the leading terms in $\alpha_S(t)$ only.] The function f is the contribution of ladder diagrams which will be discussed below. The factor M_X^2 accounts for the fact that the cross section for the Pomeron-hadron-h scattering does not decrease with increasing M_X^2. The factor $1/s^2$ is due to the phase volume. Essential diagrams for the production amplitudes of the processes (1) and (2) like the generic diagrams of Figs. 2 and 3 contain a factor $1/t^2$ due to two-hard-gluon exchanges, and t in the nominator due to the integration over transverse momenta of the exchanged gluons. The factor $1/|t|^{1/2}$ in the amplitude is due to the necessity to adjust the light-cone fraction of quark 1 in the wave function of the nucleon. The momenta of the two other quarks in a nucleon are adjusted by one-hard-gluon exchange between quarks 2 and 3 (see Fig. 2). This leads to an extra suppression of the amplitude by one power of t. The additional factor $\tilde{x}G_h(\tilde{x},|t|)$ is due to the kinematics which dictates that hard diffraction processes result from the interaction of hard gluons in the t channel with partons in hadron h carrying a small fraction $\tilde{x}$ of the hadron momentum. We want to point out that although $\tilde{x}G_h(\tilde{x},|t|)$ is practically unknown experimentally for $\tilde{x} \ll 1$, perturbative QCD predicts a rapid increase of this function at $\tilde{x} \to 0$.[3] The factor $\tilde{x}G_h(\tilde{x},|t|)$ in Eq. (5) is the hard-scattering equivalent of the factor $(M_X^2)^\Delta$ in Eq. (4) which is characteristic of a soft bare Pomeron. Some additional slow decrease with t of the differential cross section is due to the Sudakov-type form factors ($\simeq \exp[-\alpha_S(\mu^2)\times(3\pi)^{-1}\ln^2(|t|/\mu^2)]$) in the vertexes for the hard gluon-quark interactions since quarks bound in a nucleon have virtuality $\sim\mu^2$. In contrast to the case of elastic scattering considered in Refs. 4 and 5, this form factor is present in only one of two vertices for the hard interaction of quarks with gluons. Besides, it is a slower function of t because in our case one of the interacting quarks is far off the mass shell. In the elastic-pp-scattering case taking account of the Sudakov form factor leads to an additional decrease roughly as t^{-2} for $t \approx -10$ GeV^2;[5] hence we expect that in our case this effect should contribute much less than one power of t^{-1}.

A comment is in order. Contributions to the diffractive process from the diagrams which correspond to average interquark distances in the interacting nucleon, such as the exchange in the t channel by three hard gluons (such diagrams are popular in the theoretical description of the elastic pp scattering[4]), are suppressed in our case by one extra power of t^2 as compared to the diagrams of Figs. 2 and 3.

It was found in Ref. 2 that the sum of ladder diagrams increases at $\alpha_S\ln(s/\mu^2) \gg 1$, but $|t|/s \ll 1$ as

$$f(s/\mu^2,t) \sim s^{1+\omega_0}/(\alpha_S\ln s)^{3/2}, \tag{6}$$

where $\omega_0 = \alpha_S(t)12\ln(2)/\pi$. It is not yet well understood what physics will stop such a rapid increase with s of the perturbative contribution which corresponds to the fixed-cut singularity in the angular momentum plane. This is one of the long-standing unresolved problems in perturbative QCD (as well as any other gauge theory!). (For discussion of the history of this problem and references, see Ref. 6).

Applying Eq. (6) to the diffractive processes at large t we find in the leading $\alpha_S\ln(s/M_X^2)$ approximation that the cross section of these processes should rapidly increase with s (with x at $x \to 1$):

$$\frac{d\sigma}{dt\,dx} \sim \frac{\alpha_S^6(t)}{t^5}\frac{(s/M_X^2)^{1+2\omega_0}}{\ln^3(s/M_X^2)}\tilde{x}G_H(\tilde{x},|t|) = \frac{\alpha_S^6(t)}{t^5}\frac{\tilde{x}G_h(\tilde{x},|t|)}{(1-x)^{1+2\omega_0}\ln^3[1/(1-x)]}, \tag{7}$$

where $\tilde{x} = |t|/M_X^2$.

It is important for this and the above conclusions that the ladder diagrams contain no double-logarithmic terms like $\omega_0\ln(s/M_X^2)\ln(|t|/\mu^2)$.[7] So the only condition for the applicability of Eq. (7) is $\omega_0\ln(s/M_X^2) \gg 1$. Thus the predicted increase of the cross section with s (or at $x \to 1$ but large M_X^2,t) is much more rapid than that for soft processes [Eq. (4)] and than the observed increase of σ_{nH}^{tot} with s (or the increase of the hadron inclusive spectrum at $x \to 1$ but fixed large M_X^2 and small t). In Eqs. (6) and (7) for numerical estimates we use $\alpha_S(t)$ at the scale t (though the virtualities in the gluon lines are somewhat smaller, $\sim t/4$).

It is worth emphasizing that the smallness of the coupling constant at large t is a serious reason in favor of the applicability of Eq. (7) for the description of hard diffractive processes in a wide region of x not extremely close to 1. Such reasoning is inapplicable for the description of soft hadron processes ($\sigma_{hN}^{\rm tot}$) where the coupling constant is not small. A natural estimate for the kinematics where perturbative QCD may dominate in hard diffractive processes follows from the condition that virtualities of all exchanged gluons ($\sim|t|/4$) should be larger than 1 GeV^2, i.e., $|t|\geq 4$ GeV^2.

It has been suggested in Ref. 8 that reaction (2) in the kinematical domain (3) which contains jets with large transverse momentum p_t would give information on the parton structure of the Pomeron. The authors of Ref. 8 considered two options for the dependence of the cross section of reaction (2) on the fraction of the Pomeron momentum, $x_{\mathcal{P}}$: $x_{\mathcal{P}}G_{\mathcal{P}}(x,Q_0^2)\sim(1-x_{\mathcal{P}})^n$ with $n=5$ and $n=1$ at the normalization point $Q_0^2\sim 1$–4 GeV^2 (actually the Q^2 evolution of $G_{\mathcal{P}}$ was neglected). A quantitative theoretical analysis of reaction (2) based on various assumptions for the x dependence of $G_{\mathcal{P}}$ has been made in Ref. 9. In Ref. 9 the t dependence of n was not discussed.

The consideration of the diagram of Fig. 3 shows that for $1-x_{\mathcal{P}}\gg\tilde{x}$, $x_{\mathcal{P}}\gg\tilde{x}$, the distribution of gluons in the perturbative Pomeron is

$$x_{\mathcal{P}}G_{\mathcal{P}}(x_{\mathcal{P}},|t|)\sim[1/(1-x_{\mathcal{P}})]yG_h(y,|t|)\,, \tag{8}$$

where $y\simeq|t|/[M_X^2(1-x_{\mathcal{P}})]$. This behavior is a consequence of the possibility for Regge pole kinematics of neglecting the dependence on $x_{\mathcal{P}}$ in the gluon propagators in the ladder (in the Pomeron). The factor $[1/(1-x_{\mathcal{P}})]yG_h(y,|t|)$ accounts for the high-energy behavior of the cross section for gluon-hadron-h scattering in perturbative QCD. Accounting for the radiation of hard gluons with virtualities from $Q_0^2=|t|$ up to $Q^2\sim M_{\rm jet}^2$ would lead to a flatter distribution.

At the same time this distribution should be much harder than the distribution in the low-t Pomeron. For example, if one uses the model[10] in which the triple-Pomeron coupling at low t is dominated by the interaction of three Pomerons via the triangular pion-exchange diagram, then the effective gluon distribution should be softer than the gluon distribution in the pion $[x_\pi G_\pi(x_\pi,Q_0^2)\sim(1-x_\pi)^3]$. In fact, the current data[11] taken at $-t\sim 1$ GeV^2 are consistent with a quite soft behavior of $x_{\mathcal{P}}G_{\mathcal{P}}(x_{\mathcal{P}},Q^2)\sim(1-x_{\mathcal{P}})^5$.

To summarize, Eqs. (5)–(8) show that perturbative QCD predicts rather peculiar behavior of the hard diffractive processes.

We are indebted to A. Mueller for the fruitful discussion of the asymptotic behavior of diffractive processes in perturbative QCD, to L. N. Lipatov for the discussion of the asymptotic behavior of the ladder diagrams in QCD, to M. G. Ryskin for the information on the current knowledge of the soft diffractive processes, and also to J. Bjorken and P. Schlein, who drew our attention to the problem of the parton structure of the Pomeron. One of us (M.S.) is indebted to the hospitality of the theory division of the Continuous Electron Beam Accelerator Facility where this work was completed.

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