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Pomeron-Nucleon Coupling in QCD*

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Abstract The Pomeron-nucleon coupling vertex is theoretically derived from the fundamental theory of strong interaction, QCD. The empirical vertex $\beta\gamma^{\mu}F_1(t)$ used commonly in diffractive processes with a coupling strength $\beta=6.0\text{GeV}^{-1}$ is initially obtained. Our study not only reproduces the Pomeron-nucleon coupling from QCD but also clearly shows the gluonic origin and glueball nature of Pomeron. From this investigation together with the results of our previous study, we may claim that the Pomeron could be regarded as a Reggeized tensor glueball $\xi(2230)$ with quantum numbers of $I^G J^{PC}=0^+2^{++}$ which lies on the Pomeron trajectory $\alpha_{\text{P}}(t=M_{\xi}^2)=2$. Consequently, longstanding puzzle that no physical particle lies on the Pomeron trajectory seems to be solved.

Key words Pomeron, gluon, glueball, QCD, coupling vertex of Pomeron

1 Introduction

The diffractive process has become a hot and fashionable subject for studying new physics[1]. This process has been successfully described by the Regge Theory[2]. However, Regge trajectory of established hadrons are not consistent with high energy data[3]. Early, in the attempt to fit experiment with phenomenological Regge models, it was suggested that an additional Regge trajectory that could correspond to a particle with quantum numbers $I^G J^{PC}=0^+2^{++}$ at its lowest energy was needed. In order to fit the behavior of high energy ($\sqrt{s}$) elastic or diffractive cross sections, the pole position in the J-plane, $\alpha(t)$, of the Regge pole that dominates high energy scattering should have the property that $\alpha_{\text{p}}(0)\doteq 1.0$, intercept of the Regge trajectory $\alpha_{\text{p}}(t)$[4]. This is the Pomeron.

There has been a problem in understanding Regge phenomenology and high energy elastic and diffractive scattering, since none of the Regge trajectories for t-channel exchange associated with the known mesons can fit into the Pomeron trajectory with $\alpha_{\text{p}}(0)\simeq 1.0$. There have been many conjectures about the nature of Pomeron, but the dynamics leading to Pomeron is still not understood. As was observed by a number of work in this field[3], it seems that there is no simple resonance or pole on the Pomeron trajectory.

A phenomenological Pomeron exchange model with vector-type Pomeron-nucleon vertex was proposed[5]

$$V^{P-N}=\beta\gamma^{\mu}F_1(t), \tag{1}$$

where $F_1(t)$ is the isoscalar nucleon form factor and is taken to be the dipole form

$$F_1(t)=\frac{4M_{\text{N}}^2-2.8t}{4M_{\text{N}}^2-t}\cdot\frac{1}{(1-t/0.7)^2}. \tag{2}$$

The β in Eq.(1), as an input parameter, stands for the coupling strength of the Pomeron to nucleon (sometime, $\beta=3\beta_0$ with β_0 being the coupling strength of

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the Pomeron coupling quark. The factor 3 stems from quark numbers inside the nucleon according to quark counting rule). The value of the β parameter has been determined in a number of fits to high energy experimental data. Good fits to proton-proton and proton-antiproton elastic scattering, diffractive dissociation and ρ-meson electro-production have been obtained with a value of the β being

$$\beta = 6.0\mathrm{GeV}^{-1}. \tag{3}$$

According to the Regge theory, the Pomeron trajectory, $\alpha_{\mathrm{p}}(t)$, related to the propagator of Reggeon in the s-channel and to a physical particle or resonance in t-channel can be expressed as

$$\alpha(t) = \alpha_{\mathrm{p}}(0) + \alpha'_{\mathrm{p}} \cdot t, \tag{4}$$

with $\alpha_{\mathrm{p}}(0) = 1.08$ and $\alpha'_{\mathrm{p}} = 0.25\mathrm{GeV}^{-2}$. This trajectory produces a good description of diffractive processes in terms of a propagator $G_{\mathrm{p}}(s,t) = -\mathrm{i}(\alpha'_{\mathrm{p}} \cdot s)^{\alpha(t)-1}$. However, no physical particle, so far, could be identified to the Pomeron with the intercept $\alpha_{\mathrm{p}}(0)$ greater than 1.0.

Many theorists have claimed that the Pomeron exchange is related in some way to the exchange of color singlet bound state of gluons. In QCD, the candidate for vacuum exchange with properties similar to the Pomeron is the two interacting gluons' exchange. The attempts to model the Pomeron in terms of two gluons have been performed[6] and the non-perturbative part of the gluon propagator has been related to the gluon condensate of the QCD vacuum state[7]. A fairly good understanding for the cross section of pp elastic scattering at high energies[8] and reactions $p(\mathrm{e},\mathrm{e}',\rho)p$, $p(\mu,\mu',\rho)p$ at $\sqrt{s} = 10\mathrm{GeV}$ has been achieved in this framework[9].

Inspecting all results of theoretical studies, we realize that both of the two models, the Pomeron exchange and the two-gluon exchange, produce an identical fit to the existing data. The two models not only give the same right magnitude but also reproduce a good momentum dependence of the existing cross sections of vector meson electro-production in the light-quark sector (ρ, ω) as well as in the strange-quark sector ϕ[10]. This consistence and success evidently tell us that the two-gluon exchange may be responsible for the Pomeron exchange in diffractive processes.

On the other hand, the final state configuration of diffracive electro-proton interaction requires that these processes must be mediated by exchange of a "color-singlet configuration" between proton and virtual photon, since virtual photon has no color. There have been many discussions on the problems, associated with the origin and/or the properties of such "colorless objects". In the recent letter[11], the author proposed that the "colorless objects" are "color-singlet gluon clusters" due to self-interaction of gluons. Ref. [12] has also claimed that the Pomeron is a "color ball", the color-singlet complex object consisting of an arbitrary number of gluons. Of course, the leading term is the "color ball" consisting of two interacting gluons-glueball.

Furthermore, Ref. [13] has pointed out that the two-gluon exchange dominates hadron-hadron scattering at high energies and can give a remarkably good description of data for all the values of momentum transfer t. Ref. [14] has formulated the exchange of two gluons interacting with each other based on the DGLAP evolution equation. In 1987, Ref. [15] also clarified that the "two interacting gluons system" has all the properties that the Pomeron should possess. These facts evidently imply that the Pomeron is most likely identical to a two-gluon bound state-glueball, which is a colorless object and could mediate the interaction between a pair of quarks. At the same time, the BES Collaboration[16] and MARK III group[17] have claimed in 1996 and 1986 respectively that they have observed a possible existence of the glueball in both non-strange and strange decay modes of the tensor glueball state $\xi(2230)$.

With all the new developments mentioned above, we are stimulated to consider the relationship between glueballs and the soft Pomeron. However, the scalar glueball cannot be a candidate of Pomeron since it does not lie on the Pomeron trajectory which is most important for high energy physics. The tensor glueball with mass of 2.23GeV and quantum numbers $I^G J^{PC} = 0^+ 2^{++}$ does lie on the Pomeron trajectory, $\alpha_{\mathrm{p}}(t = M_{\xi}^2) = 2$[18]. Moreover, the process of exchanging scalar particle is not a diffractive process, which also asymptotically becomes less and less important as the energy increases. The odderon consisting of three gluons, a purely three-gluon bound state, is also not a candidate of the Pomeron since it does not lie on the Pomeron trajectory. Furthermore, the existence of odderon seems to be ruled out experimentally. Therefore, the only candidate for being the Pomeron seems most likely to be the tensor glueball $\xi(2230)$ with quantum numbers $I^G J^{PC}=0^+2^{++}$.

In our previous work[19], we initially proposed that the long-sought Pomeron could be a Reggeized tensor glueball $\xi(2230)$ with quantum numbers of $I^G J^{PC}=0^+2^{++}$. Within this Reggeized glueball picture of the Pomeron, the cross sections of proton-proton elastic scattering at high energies have been calculated for different incident energies[19]. This picture reproduced the existing data quite successfully. Therefore, it could be thought of as being a strong support to our physical idea that Pomeron can be regarded as a tensor glueball. The calculations of Ref. [19] also preclude the spin of the tensor glueball $\xi(2230)$ to be 4, since when $J=4$, the total decay width $\Gamma_\xi^{\rm tot}$ is too small ($\approx$1.0MeV). The spin J must be 2. With these progresses, we further found that the decay width of $\xi(2230)$ into $\rm p\bar{p}$ channel, $\Gamma_{\xi\to \rm p\bar{p}}$, should be about 1.0MeV which is expected by experimentalists. Since the Reggeized tensor glueball lies on the Pomeron trajectory of $\alpha(t)=1.08+0.20\text{GeV}^{-2}\cdot t$, the longstanding puzzle that no known physical particle lies on the Pomeron trajectory seems to be resolved too.

Based on the above successes, we study the Pomeron-nucleon coupling vertex from QCD in this paper. That is, the objective of the present paper is to attempt to derive the vertex $V^{P-N}=\beta\gamma^\mu F_1(t)$ in a non-perturbative QCD approach. In Sect. 2, we derive the coupling strength β in QCD by using the QCD sum rule, while Sect. 3 is devoted to derivation of vector coupling form γ^μ. Finally, Sect. 4 is reserved for the concluding remarks stemming from the study.

2 Coupling strength of the Pomeron to nucleon

Since the Pomeron could be a Reggeized tensor glueball with quantum numbers of $I^G J^{PC}=0^+2^{++}$ and mass of 2.23GeV which has been most likely observed by MARK-III[17] in 1986 and BES Collaboration[16] in 1996, respectively, and the glueballl does fit into the Pomeron trajectory and has all the properties that the Pomeron has. We try to work out the Pomeron -nucleon coupling strength β from QCD in this section.

In order to do so, we use the methods developed for deep inelastic scattering to derive the glueball-nucleon coupling strength. Recall that the inclusive deep inelastic scattering (DIS) cross section can be obtained from forward Compton scattering[20], $\gamma+\rm p\to\gamma+p$, by using an operator product expansion in a light-cone representation. The hadronic tensor for a proton target is

$$W_{\mu\nu}=\frac{1}{2\pi}{\rm Im}[T_{\mu\nu}], \tag{5}$$

with

$$T_{\mu\nu}={\rm i}\int {\rm d}^4x{\rm e}^{ikx}\langle p|T[J_\mu(x)J_\nu(0)]|p\rangle, \tag{6}$$

where the electromagnetic current $J_\mu(x)=\bar{q}(x)Q\gamma^\mu q(x)$ with Q being the charge operator. In analogy to DIS, we evaluate $T_{\mu\nu}$ using the diagram shown in Fig. 1. Introducing a light-cone representation with momentum $(K^+,\boldsymbol{K}^\perp,K^-)$, one finds in the scaling region

$$W_{+,-}={\rm i}\frac{2}{\pi}\int {\rm d}x^-{\rm e}^{{\rm i}k^+x^-}\langle p|T[q_-^\dagger(x_-)Q^2q_-(0)]|p\rangle, \tag{7}$$

where q_- is a light-cone projection of the quark field. The expression in Eq. (7) gives the parton model for the structure functions, with $W_{+,-}=F_2(x)/2x$ expressed in parton distribution functions $F_2(x)$ with the x being the scaling variable.

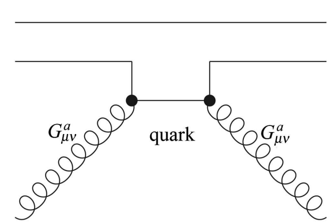

Fig. 1. Diagrammatic representation of glueball coupling to quark for high energy elastic scattering.

Let us consider the forward gluon-proton scattering T-matrix

$$T = \mathrm{i}\int \mathrm{d}^4x\mathrm{d}^4y\mathrm{e}^{\mathrm{i}k(x-y)}\langle p|T[J_\mathrm{c}(x)J_\mathrm{c}(y)]|p\rangle, \tag{8}$$

with the color current

$$J_\mathrm{c}(x) = \bar{q}(x)\gamma^\mu A_\mu(x)q(x). \tag{9}$$

This is the analog to the forward Compton T-matrix with the electromagnetic potential replaced by the gluonic color potential. We use the fixed point gauge, $x_\mu A^\mu(x) = 0$, and $A_\mu(x) = -\frac{1}{2}G_{\mu\nu}(0)x^\nu$, with $G_{\mu\nu} = \sum_{a=1}^{8}\tau^a G^a_{\mu\nu}$, and τ^a being the $SU(3)$ color operator. Keeping the lowest-dimension contractions one finds the standard form

$$T = \frac{\mathrm{i}}{4}\frac{\partial}{\partial k^\alpha}\frac{\partial}{\partial k^\beta}\mathrm{i}\int \mathrm{d}^4x\mathrm{d}^4y\mathrm{e}^{\mathrm{i}k(x-y)}\times$$
$$Tr[S_\mathrm{q}(-x)\gamma^\mu S_\mathrm{q}(x)\gamma^\nu\langle 0|g^2G_{\mu\alpha}G_{\nu\beta}|0\rangle]. \tag{10}$$

Proceeding as in DIS, and making use of $\frac{\partial}{\partial k}s_{\mathrm{q}(k)} \rightarrow S_\mathrm{q}/m_\mathrm{q}$ in the limit $k \rightarrow 0$, one finds

$$T \simeq K\frac{\partial}{\partial k^+}\int \mathrm{d}x\mathrm{e}^{\mathrm{i}kx}S_\mathrm{q}(x), \quad K = \frac{2a}{27m_\mathrm{q}\lambda}. \tag{11}$$

Taking the mean value of the quark mass to be 8MeV, $a = 4\pi^2\langle 0|\bar{\mathrm{q}}\mathrm{q}|0\rangle \simeq 0.55\mathrm{GeV}^3$, and $\lambda = \langle 0|J_{GB}|GB\rangle$ being a normalization factor given in Ref. [21]. We find the coupling parameter in $V^{GB-N}(t \rightarrow 0)$ to be

$$\beta = 6.6\mathrm{GeV}^{-1}, \tag{12}$$

which is comparable to the empirical values $6.0\mathrm{GeV}^{-1}$ given in Eq. (3) and used widely in literature. From this prediction, we have a good reason to conjecture that the Pomeron may originate from gluonic degrees of freedom.

3 Coupling form of the Pomeron to nucleon

According to the above discussions, the Pomeron coupling to quark, as shown in Fig. 2(a), is identical to the tensor glueball $\xi(2230)$ coupling to the quark as shown in Fig. 2(b). Fig. 2(b) clearly shows that the glueball-quark coupling vertex can be derived from studying the gluon-quark scattering

$$\mathrm{q}(p_1) + \mathrm{g}_a(q_1) \rightarrow \mathrm{q}(p_2) + \mathrm{g}_b(q_2). \tag{13}$$

That is, from calculations of the diagram for the amplitude of quark-gluon scattering of Eq. (13), we can get the coupling vertex in Fig. 2(b). The diagram of Fig. 2(b) can be decomposed into three terms: t-channel gluon-quark scattering, u-channel gluon-quark scattering, and s-channel gluon-quark scattering as shown in Fig. 3.

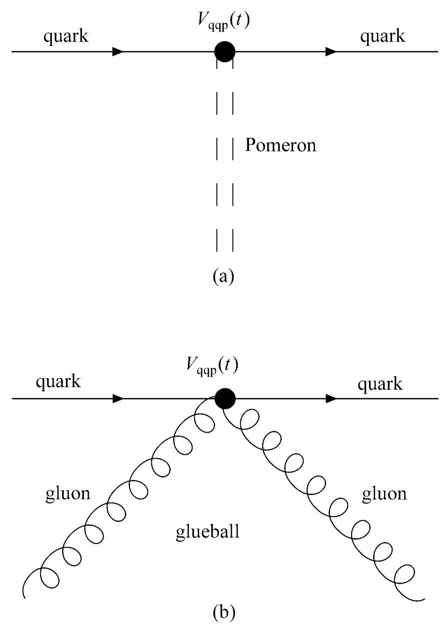

Fig. 2. Description of the pomeron quark interaction vertex.
(a)Pomeron-quark coupling in the conventional Regge picture; (b)Glueball-quark coupling in the QCD picture.

The Greek letters in Fig. 3, μ, ν, λ, ..., are Lorentz tensor indices, a, b, c are gluon color indices (a, b, $c = 1, 2, \ldots, 8$), $i, j, k, l (= 1, 2, 3)$ are quark color indices, k, p, q, l label 4-momentum, and $\varepsilon^{\mu,(\nu,\lambda)}$ are gluon polarization vectors.

In order to calculate the amplitudes of the three diagrams in Fig. 3, we refer readers to looking at the Feynman rules of QCD. We define the Mandelstam variables of the processes as follows:

$$s = (p_1 + q_1)^2, \quad t = (p_1 - p_2)^2, \quad u = (p_1 - q_2)^2, \tag{14}$$

and then we write down the invariant amplitudes for the three different diagrams in Fig. 3 according to the Feynman rules of QCD. The t-channel amplitude of the diagram in Fig. 3(a) is given by

$$m_t(\mathrm{q}_i\mathrm{g}_a \rightarrow \mathrm{q}_j\mathrm{g}_b) = \frac{g^2}{t}(f^{abc}\cdot t^\mathrm{c}_{ji})\cdot$$
$$[\varepsilon_\sigma(q_2)C^{\mu\rho\sigma}\varepsilon_\rho(q_1)] \times [\bar{u}(p_2)\gamma_\mu u(p_1)], \tag{15}$$

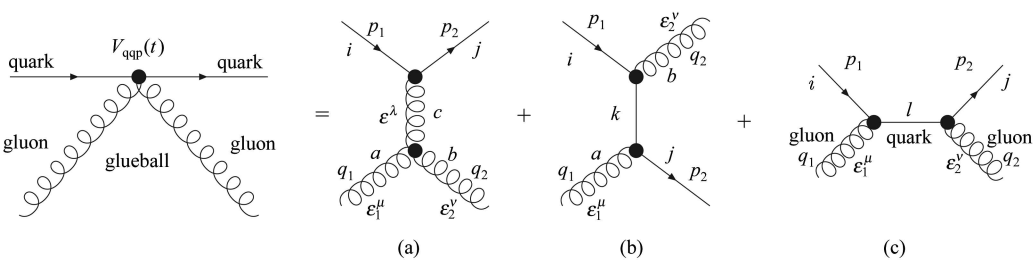

Fig. 3. Gluon-quark scattering.
(a) t-channel scattering; (b) u-channel scattering; (c) s-channel scattering. The solid lines in the figure stand for quarks, the curly lines represent gluons, and the full circles are coupling vertexes of gluon-quark or gluon-gluon in QCD.

where

$$C^{\mu\rho\sigma} = g^{\mu\rho}(p_1 - p_2 + q_2)^\sigma + g^{\rho\sigma}(-q_2 - q_1)^\mu + g^{\sigma\mu}(q_1 - p_1 + p_2)^\rho. \tag{16}$$

The u-channel amplitude of the diagram in Fig. 3(b) is formalized as the following

$$m_u(\mathrm{q}_i \mathrm{g}_a \to \mathrm{q}_j \mathrm{g}_b) = -\frac{\mathrm{i}g^2}{u} t^b_{ik} t^a_{kj} \bar{u}_j(p_2) \not{\epsilon}_1 (\not{p}_1 - \not{q}_1) \not{\epsilon}_1 u_i(p_1), \tag{17}$$

and finally, the s-channel amplitude of the diagram in Fig. 3(c) can be expressed by

$$m_s(\mathrm{q}_i \mathrm{g}_a \to \mathrm{q}_j \mathrm{g}_b) = -\frac{\mathrm{i}g^2}{s} t^b_{il} t^a_{lj} \bar{u}_j(p_2) \not{\epsilon}_2 (p_1 + q_1) \not{\epsilon}_1 u_i(p_1), \tag{18}$$

Therefore, the total scattering amplitude $m_{\mathrm{q+g \to q+g}}$ is given by summing over all three terms,

$$m_{\mathrm{q+g \to q+g}} = m_t + m_u + m_s. \tag{19}$$

However, our calculations show that the t-channel contribution dominates the cross section, while s- and u-channels give a tiny contribution and can be neglected. Thus, taking the t-channel contribution (the contribution from the diagram in Fig. 3(a)) into consideration is sufficiently enough. At the same time, since the Pomeron corresponds to a t-channel physical object and has nothing to do with the u- and s-channel exchange, the only surviving channel contributing dominantly to the amplitude is naturally the t-channel. We only need to consider the t-channel contribution in the calculations of Fig. 3. Thus, as a consequence of Eq. (15), it is evident that the Pomeron couples to quark with a vector coupling form, γ^μ. That is, Pomeron behaves like an isoscalar photon. Then, the coupling vertex of the Pomeron to nucleon is given by multiplying m_t by a factor of 3 due to quark counting rules. It should be emphasized that our result on the vector coupling form is consistent with the lattice QCD calculations[22]. According to the lattice QCD calculations, the amplitude of the diagram on the right hand side of Fig. 3 is given by

$$\frac{\mathrm{i}}{2}\delta_{\alpha\beta} g^2 \{t^c, t^b\}_{jl} \cdot \gamma^\mu \cdot \sin[\frac{a}{2}(p_\mu + q_\mu)], \tag{20}$$

where a is lattice space. Eq. (20) evidently shows that the glueball-quark coupling has a γ^μ form. That is, the lattice calculations again reproduce the γ^μ coupling vertex of the glueball-quark interaction. Since the lattice calculation has been thought of as being a reliable prediction, we think that our discussions have given a good understanding of the Pomeron-nucleon coupling vertex in QCD.

4 Discussion and concluding remarks

We briefly recall the results of investigation both in the Pomeron exchange model and the two-gluon exchange model for diffractive processes, which makes us to believe that the Pomeron could be a tensor glueball $\xi(2230)$ with quantum numbers of vacuum $I^G, J^{PC} = 0^+, 2^{++}$ which lies on the Pomeron trajectory $\alpha_{\mathrm{p}}(t) = 1.08{+}0.20\mathrm{GeV}^{-2}t$. Based on this assumption, the empirical vector coupling vertex $V^{P-N} = \beta\gamma^\mu F_1(t)$ of the Pomeron to nucleon is obtained from the calculations of strong interaction QCD. The empirical coupling strength $\beta = 6.0\mathrm{GeV}^{-1}$ and the vector coupling form, γ^μ used widely in literature are obtained theoretically. The results show that the Pomeron indeed behaves rather like a $c' = +1$ isoscalar photon conjectured by many. Needless to say, this study also reveals the gluonic origin and glueball nature of the Pomeron so that the longstanding puzzle that no particle lies on the Pomeron trajectory seems to be solved.

On the other hand, it should be pointed out that the dipole form factor $F_1(t)$ in Eq. (2) violates the crossing symmetry law since $F_1(t)$ has poles and cannot be an analytic function of Mandelstam variable. Therefore, it cannot be used in dealing with crossing symmetry between different channels. A good form factor for crossing channel study has been proposed by us in Ref. [19], which has a good behavior and satisfies the crossing symmetry. We strongly recommend readers to use the relativistic, singularity free form factor given by Ref. [19] in any crossing channel study.

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在量子色动力学中坡密子与核子的耦合*

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摘要 用强相互作用的基本理论量子色动力学推导出了坡密子与核子的耦合顶点，得到了在绕射过程的研究中广泛应用的，耦合强度$\beta=6.0\mathrm{GeV}^{-1}$的经验的耦合顶点$\beta\gamma^{\mu}F_1(t)$. 本研究也清楚地表明了坡密子的胶子起源和胶子球的粒子性本质，这是一个长期没有解决的问题. 结合我们以前的研究结果，我们认为坡密子可能是一个在雷其轨迹$\alpha(t)=1.08+0.20\mathrm{GeV}^{-2}t$上，具有量子数$I^GJ^{PC}=0^+2^{++}$的雷其化的张量胶子球. 所以在雷其轨迹没有物理粒子的困难似乎得到了解决.

关键词 坡密子 胶子 胶子球 QCD 坡密子核子耦合

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