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Gluonic effects in vector meson photoproduction at large momentum transfers

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Abstract

Non-perturbative QCD mechanisms are of fundamental importance in strong interaction physics. In particular, the flavor singlet axial anomaly leads to a gluonic pole mechanism which has been shown to explain the η' mass, violations of the OZI rule and more recently the proton spin. We show here that the interaction derived from the gluonic pole exchange explains the high momentum transfer behavior of the photoproduction cross sections of vector mesons at JLab energies.

1 Introduction

Recently the CLAS Collaboration at JLab has published new data on ρ- and ϕ-meson photoproduction at large momentum transfers [1, 2]. The main goal of these data is to provide understanding for the mechanism responsible for the violation of the OZI rule in strong interactions [3, 4, 5].

The usual approach to the description of exclusive reactions consists in the use of some effective non-perturbative reaction model at small momentum transfers and hard perturbative gluonic exchange mechanisms at large momentum transfers [6]. These approaches are unable to explain the large spin effects at large $-t$ in exclusive reactions [7]. One example is the large A_{nn} asymmetry in proton-proton elastic scattering which can be understood only if some helicity violating contribution is present at such momentum transfers. The pQCD exchanges in these approaches lead only to quark helicity conserving contributions and therefore can not be the dominant mechanisms for exclusive reactions in the few GeV region.

We have proposed a non-perturbative mechanism [8] for exclusive reactions at large momentum transfers, whose relevance we have studied in ϕ meson electromagnetic production at large momentum transfer, which we here generalize to ρ- and ω-meson photoproduction off the nucleon. The new ingredient of our model is the gluonic contribution arising from the QCD mechanism associated with the flavor singlet axial anomaly and describable in terms of an additional gluonic pole in the amplitudes. The gluonic pole was introduced in [10] to describe features of OZI violation in the pseudoscalar meson nonet. It has been shown to provide a natural explanation of proton spin [11]. Recently, applications to radiative decays of pseudoscalar mesons, the muon anomalous magnetic moment and the determination of the photon structure g_1^γ function in polarized deep inelastic scattering have been discussed [9]. The origin for this pole is the periodicity of QCD the potential as a function of the topological charge and the existence of instantons tunneling between the various classical vacua of the theory [12].

By showing the relevance of the gluonic pole exchange in vector meson photoproduction at large momentum transfers, we unveil a non-perturbative QCD effect, which

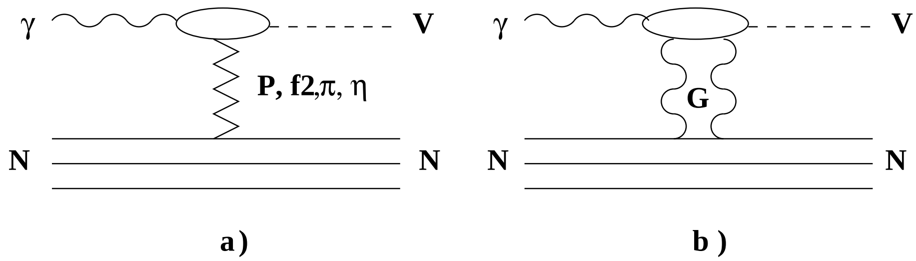

Figure 1: a) Contributions from the pomeron, f_2, π (η) to ρ and ω (ϕ) photoproduction; b) Contribution from the G-pole exchange to vector-meson photoproduction.

is neither contained in the low energy effective theories nor in the pQCD ingredients of previous calculations.

2 Vector meson photoproduction off the nucleon

It is very well known that at large energy and small momentum transfer the main contribution to the photoproduction of the vector mesons comes from the pomeron exchange. In the low energy region one can expect the dominance of the pomeron at small $-t$ only for ϕ meson electromagnetic photoproduction due to OZI rule. For ρ and ω-meson production the contribution from secondary Reggeon exchanges might be important. In the case of photoproduction the leading Regge trajectory with appropriate quantum numbers is the f_2 meson trajectory. Subleading Regge exchanges, which might give a significant contribution, are π-meson exchange for ρ- and ω-meson production and η-meson exchange for ϕ-meson production [3] (Fig.1a).

We use the Donnachie-Landshoff (DL) model [13] to describe the soft pomeron contribution to the vector meson production differential cross section,

$$\frac{d\sigma_P}{dt} = \frac{81 m_V^3 \beta_0^2 \beta_q^2 \Gamma^V_{e^+e^-}}{\pi \alpha_{\rm em}} \frac{F(t)^2 \mu_0^4}{(2\mu_0^2 + Q^2 + m_V^2 - t)^2 (Q^2 + m_V^2 - t)^2} \left(\frac{S}{S_0}\right)^{2\alpha_P(t)-2}, \quad (1)$$

where

$$F(t) = \frac{4M_N^2 - 2.8t}{(4M_N^2 - t)(1 - t/0.7)^2} \quad (2)$$

is the electromagnetic nucleon form factor. The pomeron-quark couplings $\beta_0 = 2$ GeV^{-1}, $\beta_s = 1.5$ GeV^{-1} are obtained from a fit to the total pp, πp and Kp cross sections [14], $\mu_0^2 = 1.1 GeV^2$, $S_0 = 4 GeV^2$ and the pomeron trajectory is $\alpha_P(t) = \alpha_P(0) + \alpha'_P t$, with $\alpha_P(0) = 1.08$ and $\alpha'_P = 0.25$ GeV^{-1}. The effect of the f_2 trajectory can be taken into account by multiplying the equation for the pomeron contribution Eq.(1) by the factor

$$F_{P+f_2} = 1 + 2A(S,t) cos\left(\frac{\pi}{2}(\alpha_{f_2}(t) - a_P(t))\right) + A(S,t)^2 \quad (3)$$

with

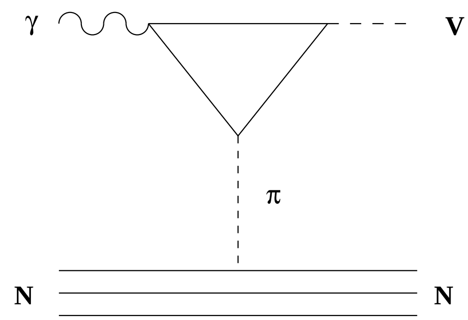

Figure 2: Contribution of the triangle graph to the π exchange amplitude.

$$A(S,t) = \frac{\beta_{f_2}^2}{\beta_0^2}\left(\frac{S}{S_1}\right)^{\alpha_{f_2}(t)-1}\left(\frac{S}{S_0}\right)^{1-\alpha_P(t)}, \tag{4}$$

where the f_2 trajectory is $\alpha_{f_2}(t) = 0.55 + 0.9t$, and the coupling to quarks $\beta_{f_2} = 4.32$ was taken also from the DL fit to the total hadron cross sections [14].

The contribution of the pseudoscalar exchange to the cross section can be calculated by using the same procedure as in the DL approach to the pomeron contribution [13] [1]

Direct calculation of the triangle diagram in Fig.2 [2] at the quark level with the quark-meson interactions

$$\begin{aligned} L_{\pi qq} &= \frac{g_{\pi^0 qq}}{2m_q}(\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d)\partial^\mu\pi^0, \\ L_{\eta ss} &= \frac{g_{\eta ss}}{2m_s}\bar{s}\gamma_\mu\gamma_5 s\partial^\mu\eta \end{aligned} \tag{5}$$

gives the result

$$\frac{d\sigma_{PS}}{dt} = -\frac{K_{PSV} m_V g_{PSNN}^4 \Gamma_{e^+e^-}^V t}{\pi\alpha_{\rm em}}\frac{FPS(t)^2}{(S-M_N^2)^2(t-M_{PS}^2)^2}, \tag{6}$$

where $K_{\pi\rho} = 3/100$, $K_{\pi\omega} = 9K_{\pi\rho}$, $K_{\eta\phi} = 3$ and we have used the constituent quark relations $2m_q = m_V$, $g_{\pi^0 qq} = 3/5 g_{\pi^0 NN}$ and $g_{\eta ss} = 2g_{\eta NN}$.

For numerical estimates the value $g_{\pi NN} = 13.28$ [15] for pion-nucleon and the $SU(3)_f$ value $g_{\eta NN} = 3.52$ for η-nucleon coupling [3] have been used. In Eq.(6) the pseudoscalar-nucleon form-factor is taken of monopole form

$$FPS(t) = \frac{\Lambda^2 - M_{PS}^2}{\Lambda^2 - t} \tag{7}$$

[1] We do not include the interaction of the η-meson with the $u-$ and $d-$ quarks because its contribution to ρ and ω-meson production is much smaller than the contribution of the π-meson.

[2] We do not use the conventional approach for the calculation of the pseudoscalar contribution which consists in using as input the experimental values of widths for $V \to \gamma\pi^0(\eta)$ [3] since one has large uncertainties in the estimates due to the poor knowledge of the $V\gamma\pi^0(\eta)$ form-factors.

with $\Lambda = 0.8 GeV$ [16]. The Reggeization of the pseudoscalar meson exchange can be perform in the standard way (see for example [17]). It is done by substituting the pseudoscalar propagator in the following way,

$$\frac{1}{t-M_{PS}^2} \rightarrow \left(\frac{S}{S_1}\right)^{\alpha_{PS}(t)} \frac{\pi\alpha'}{sin\pi\alpha_{PS}(t)} \frac{1+e^{-i\pi\alpha_{PS}(t)}}{2\Gamma(1+\alpha_{PS}(t))}. \quad (8)$$

The pseudoscalar trajectories are taken as

$$\alpha_{PS}(t) = \alpha'(t - M_{PS}^2) \quad (9)$$

with slope $\alpha' = 0.9 GeV^{-2}$.

It can be shown that the effect of Reggeization leads to the multiplication of Eq.(6) by the Regge factor

$$R = \left(\frac{S}{S_1}\right)^{2\alpha_{PS}(t)} \Gamma(1-\alpha_{PS}(t)) cos^2(\frac{\pi\alpha_{PS}(t)}{2}). \quad (10)$$

The pomeron contribution to vector meson photoproduction is shown in Figs. 3, 4 and 5 by long-dashed lines. It underestimates the low $-t$ cross-section for ρ and ω production at JLab energies but describes rather well the low $-t$ ϕ-meson production. The total contribution of the DL pomeron and f_2 exchange to the cross section for ρ and ω photoproduction is presented in Figs. 3 and 4 by dashed-dot lines. The contribution of the pion exchange in Figs. 3 and 4 and η-meson exchange in Fig. 5 is shown by short-dashed line. It is apparent that pseudoscalar exchange is important only for ω production at very small momentum transfers. Our result is in contradiction with the result of ref. [3] where a nonreggeized pion exchange contribution to vector meson production was calculated. In our approach the suppression of the pseudoscalar contribution at large $-t$ is not very sensitive to the $-t$ dependence of the $\pi(\eta)NN$ and $\pi(\eta)\gamma V$ form-factors and the absolute value of the pseudoscalar coupling with quarks. This suppression is due to the smallness of the Regge factor $(S/S_1)^{2\alpha_{PS}(t)}$ in the cross-section for large $-t$. The effect of the Reggeization for the case of the π contribution to ρ production is shown in Fig. 6. This effect is very large and can not be neglected. The pomeron and Regge contributions describe the data for all mesons rather well in the small $-t \leq 0.5$ GeV^2 region. However, for large $-t \geq 1$ GeV^2, all these contributions deviate strongly from the data.

3 Anomalous gluonic exchange

In our previous work [8] a new gluonic, so-called G-pole, exchange was introduced to explain the large $-t$ electromagnetic ϕ meson production at JLab. This exchange, not related to the exchange of any mesonic state, arises from the nontrivial topological structure of the QCD vacuum. In some sense this exchange represents the interaction of the quarks in the photon with the quarks in the proton generated by the excitations of the QCD vacuum.

In QCD the anomalous gluonic axial current

$$K_\mu = \frac{\alpha_s}{4\pi}\epsilon_{\mu\nu\alpha\beta}A_\nu^a(\partial_\alpha A_\beta^a + \frac{g_s}{3}f_{abc}A_\alpha^b A_\beta^c) \quad (11)$$

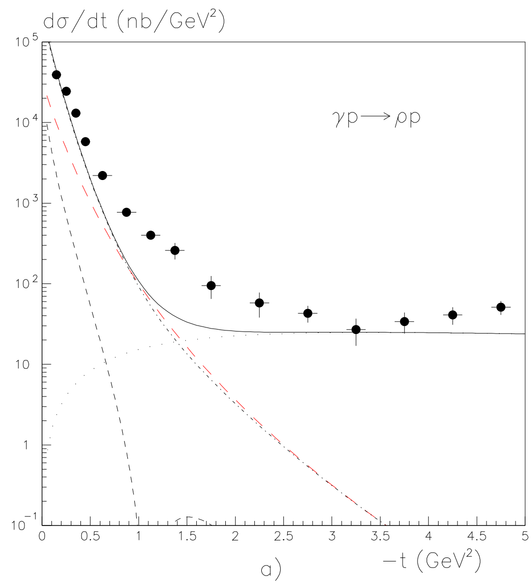

Figure 3: The contributions of the pomeron (long-dashed line), the sum of pomeron and f_2 exchanges (dashed-dot line), pion (short-dashed line) and G- exchange (dotted line) to ρ-meson production at $E_\gamma = 3.82GeV$. The solid line represents the total contribution. The data are from the CLAS Collaboration [1].

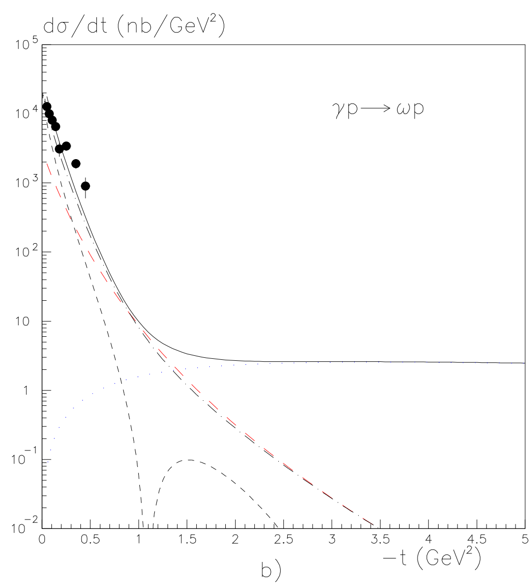

Figure 4: The contributions of the pomeron , the sum of pomeron and f_2 exchanges, pion and G-exchange to ω-meson production at $E_\gamma = 3.87GeV$. The notation follows that of the previous figure and the data are from [18].

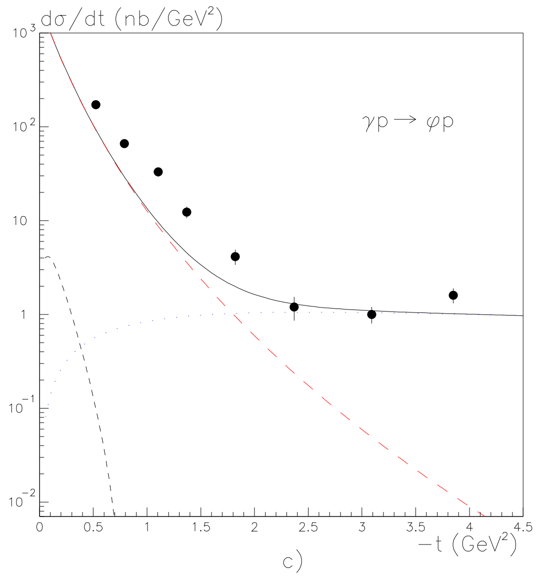

Figure 5: The contributions of the pomeron, the sum of pomeron and f_2 exchanges, η (short-dashed line) and G-exchange to the ϕ-meson photoproduction at $E_\gamma = 3.6 GeV$. The notation for the pomeron and f_2 contributions follows that of the previous figures and the data are from [2].

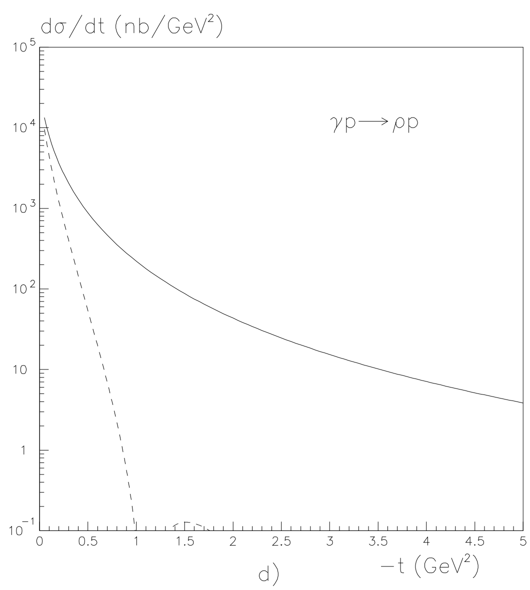

Figure 6: The effect of π reggeization in ρ production is shown.

has a massless pole

$$i \int d^4x e^{ikx} < 0|TK_\mu(x)K_\nu(0)|0 >_{k\to 0} \to \frac{g_{\mu\nu}}{k^2}\lambda^4 \quad (12)$$

which is related to the topological susceptibility of the QCD vacuum

$$\chi(0) = -\lambda^4 = i \int d^4x < 0|TQ(x)Q(0)|0 >, \quad (13)$$

where $Q(x) = \partial_\mu K_\mu$ is the density of topological charge. This pole has been called the gluonic ghost pole [10] in the literature and G-pole by us [8].

The diagonalization of the propagator matrix for the ghost operator Q and quark nonet states π^0, η^8 and η' leads to the following propagator

$$< GG >= -A \quad (14)$$

which we called G-propagator. A in Eq.(14) is determined by the topological susceptibility of QCD vacuum [9]

$$A \approx -\chi(0)|_{YM} = \frac{f_\pi^2}{6}(m_{\eta'}^2 + m_\eta^2 - 2m_K^2) \approx (180MeV)^4. \quad (15)$$

We should stress that the G-propagator Eq.(14) does not depend on the momentum transfer k^2 and therefore the effective interaction induced by the ghost exchange is *point-like*. This property is responsible for the large G-pole contribution to vector meson photoproduction at large momentum transfers as will be shown next.

Let us estimate the contribution of G-pole exchange to vector meson photoproduction (Fig.1b). To calculate this diagram the values of couplings g_{GNN} and $g_{G\gamma V}$ are needed. We will use the fact that the contribution of the G-pole to the physical amplitudes in the flavor singlet channel leads to results which are different from the predictions of the OZI rule. This mechanism produces, for the isosinglet axial-vector nucleon form factor at zero momentum transfer, the following generalized $U(1)$ Golberger-Treiman relation [19]

$$2M_N G_A^0 = F g_{\eta' NN} + 2N_f A g_{GNN} = F_{\eta_0} g_{\eta_0 NN}, \quad (16)$$

where $F \approx \sqrt{2N_f} f_\pi$, $f_\pi = 93$ MeV and g_{GNN} is G-nucleon coupling constant. The experimental value of $G_A^0 \approx 0.3$ extracted from experimental data on nucleon spin-dependent structure function $g_1(x, Q^2)$ [20], allows us to estimate the value of G-nucleon coupling constant as

$$g_{GNN} \approx -\frac{0.3M_N}{N_f A} \approx -89.35GeV^{-3}. \quad (17)$$

The G-pole contribution to the $\eta'(\eta) \to \gamma\gamma$ decay has been discussed in [19] where a modified formula for the effective coupling of the η' meson with photons has been obtained,

$$F g_{\eta'\gamma\gamma} + 2N_f A g_{G\gamma\gamma} = \frac{4}{\pi}\alpha_{em}. \quad (18)$$

Let us consider the G-pole contribution to the $\eta'\gamma V$ coupling, where V stands for ρ^0, ω and ϕ. The interaction of the vector mesons with the quarks is assumed to be photon-like

$$L_{\rho qq} = C_\rho(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d)\rho_\mu, \; L_{\omega qq} = C_\omega(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d)\omega_\mu, \; L_{\phi ss} = C_\phi \bar{s}\gamma_\mu s\phi_\mu. \quad (19)$$

Due to this vector meson-photon analogy the generalization of Eq.(18) to the case of the $\eta' \to \gamma V$ amplitude is straightforward

$$F g_{\eta'\gamma V} + 2N_f A g_{G\gamma V} = k_V C_V \sqrt{\frac{\alpha_{em}}{\pi^3}}, \tag{20}$$

where $k_\phi = -1$, $k_\rho = 3$ and $k_\omega = 1$. The values of $g_{\eta'\gamma\phi}$, $g_{\eta'\gamma\omega}$ and $g_{\eta'\gamma\rho}$ can be extracted from the experimental widths $\Gamma_{\phi\to\eta'\gamma}$, $\Gamma_{\omega\to\eta'\gamma}$ and $\Gamma_{\eta'\to\rho\gamma}$.

The vector meson couplings with quarks are not well known. In order to estimate them we use a constituent quark model calculation for the ρ and ω couplings

$$C_\rho = C_\omega = \frac{g_{\omega NN}}{3} \approx 3.45, \tag{21}$$

where $g_{\omega NN} = 10.35$ is taken from [3] and for the ϕ coupling we use the NJL model prediction [21]

$$C_\phi = -5.33. \tag{22}$$

Our final estimate for the G-vector meson couplings is $|g_{G\gamma\rho}| = 11.02$ GeV^{-4}, $|g_{G\gamma\omega}| = 3.57$ GeV^{-4} and $|g_{G\gamma\phi}| = 1.91$ GeV^{-4}.

We are now ready to calculate G-pole contribution to vector meson photoproduction. The absolute value of the G-contribution strongly depends on its couplings with the nucleon, photon and vector meson and is given by

$$\frac{d\sigma_G}{dt} = -\frac{A^2 g^2_{G\gamma\phi} g^2_{GNN} t(t - M_\phi^2)^2}{64\pi(S - M_N^2)^2} F_1(t)^2, \tag{23}$$

where $F_1(t) = 1/(1 - t/M_{f_1}^2)^2$ is the flavor singlet axial form factor of the nucleon with the value of M_{f_1} equals to the mass of the flavor singlet $f_1(1285)$-meson [8].

It should be noted that the G-exchange induces a nucleon spin-flip, which produces a factor t in Eq.(23), and leads to an additional enhancement of the G-pole contribution at large $-t$, with respect to the pomeron contribution, which is nonspin-flip Eq.(1). Moreover the energy dependence of the G contribution corresponds to that of a fixed pole with zero Regge slope. Therefore the large t Regge suppression in vector meson production given by $(S/M_N^2)^{2\alpha'_R t}$ with the slope $\alpha'_R \approx 0.9$ GeV^{-2} for the usual Regge trajectories, e.g. π^0 and η, is absent for the G-exchange.

The result of the calculation of the G-pole contribution is presented in Fig. 3, 4 and 5 by the dotted lines. The sum of the pomeron, f_2, π^0, η and G-pole contributions are shown by the solid lines. It is evident that G-exchange determines the behavior of the cross section at large $-t$ and our model based only on pomeron, secondary Regge exchange and G-pole contributions reproduces the main features of a data. The deviation from data at intermediate values of $-t$ might be related to additional contributions from the pomeron and Regge cuts or to non-linear t dependences of Pomeron and f_2 trajectories[22].

4 Conclusion

The gluonic degrees of freedom play a very important role in the ρ- ω- and ϕ-meson photoproduction at JLab energies. At small $-t$ the cross-section is described rather well by the Donnachie-Landshoff soft pomeron and secondary Regge exchanges. At large $-t$

an extremely interesting phenomena, related to the complex structure of QCD vacuum, takes place. We have shown that at large momentum transfers, the point-like interaction induced by the G- pole exchange, related to ghost pole in the correlator of the anomalous gluonic axial currents, gives the dominant contribution. We should stress that vector meson photoproduction is only one of the possible exclusive processes where the G-pole contributes. We plan to extend our considerations here to the study of other reactions at large momentum transfers.

As has been mentioned the G-pole exchange leads to a nucleon helicity flip and therefore can be separated from the helicity conserving pQCD hard gluonic exchanges in processes with polarized particles.

Recently we have shown that at large energy and large momentum transfer a new anomalous trajectory with very large intercept $\alpha_{f1} \approx 1$ and very small slope $\alpha' \approx 0$ called f_1 is needed to explain elastic pp, $p\bar{p}$ and vector meson production at HERA [23]. It would be interesting to find a relation between this f_1 trajectory and the $G-$ exchange similarly as was discussed recently for the relation between pomeron and S-channel multi-glueball 0^{++} exchange [24].

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