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EXCLUSIVE PHOTO-AND ELECTROPRODUCTION OF
VECTOR MESONS AT LARGE MOMENTUM TRANSFER

J.M. Laget, R. Mendez-Galain

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Exclusive Photo- and Electroproduction of Vector Mesons at Large Momentum Transfer

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Abstract

Two gluon exchange mechanisms are expected to govern exclusive photo and electroproduction of vector mesons at large momentum transfer. While quark interchange mechanisms may compete, at least at low energies, in the light quark sector they are strongly suppressed in the heavy quark sector. Φ meson production appears to be a promising way to study these two gluon exchange mechanisms. On the one hand, they appear to be a good candidate to explain the hard part of the Pomeron. On the other hand, they open up an almost virgin field : the study of quark correlations in hadronic matter. A possible application would be the study of hidden color components in the wave function of the ground state of few-nucleon systems.

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1 Introduction.

At low momentum transfer, exclusive (or elastic) photo- or electroproduction of vector mesons is a purely diffractive mechanism [1]. The real or virtual photon fluctuates into a vector meson which eventually elastically scatters on the hadronic target. At high energies, such an elastic scattering is mediated by the exchange of the Pomeron.

At large momentum transfer, components with small transverse size are selected in the wave functions of the vector meson, the nucleon and the Pomeron. It makes sense to couple the Pomeron to a single quark in a hadron [2], or to deal with possible constituents of the Pomeron as shown in Fig. 1.

The first attempts [3,4,5] to model the Pomeron in terms of two gluons have been improved [6,7,8,9] and the non perturbative part of the gluon propagator has been related to the gluon condensate structure of the vacuum [10]. A fair understanding of the cross section of nucleon-nucleon elastic scattering at asymptotic energies, as well as the magnitude, and the variation against the squared mass Q^2 of the virtual photon, of the cross-section of the $p(e, e'\rho)p$ [11] and $p(\mu, \mu'\rho)p$ [12] reactions, at $\sqrt{s} \simeq 10\text{GeV}$, has been achieved in this framework.

The aim of this article is to investigate the momentum dependence of the cross-section of exclusive photo- and electro-production of vector meson on the nucleon at intermediate energies. Here quark interchange mechanisms may compete with two gluon exchange mechanisms. Their contribution behaves as s^N and increases when the available energy decreases : this is consistent with the current knowledge [13] of the photoproduction of mesons and baryons made of light quarks (π , ρ , Δ ...). They are not allowed (or at least are strongly suppressed) in the photoproduction of mesons and baryons which contain a heavy (strange or charmed) quark (to the extent that the strange or the charmed component of the hadronic ground state is small enough) : these channels are dominated by two gluon exchange mechanisms.

In this respect, ϕ meson production channels appear to be particularly appealing, since the ϕ meson is primarily made of two strange quarks (different from the valence quarks of the normal nuclear matter). Also the production threshold (1.54 GeV in photoproduction) is small enough and the corresponding cross-section is large enough to allow a comprehensive study of its momentum dependence and the determination of the various spin density matrix elements, through the two Kaon decay of the ϕ .

The main result of this study is shown in Fig. 2, where the cross-section of the $p(\gamma, \phi)p$ reaction is plotted against the momentum transfer t . It turns out that the Pomeron exchange model [2] reproduces surprisingly well the existing data [14,15,16,17]. Around $-t \simeq 1 \text{ (GeV/c)}^2$, the two gluon exchange contribution

accounts for the magnitude as well as for the slope of the momentum distribution and matches the Pomeron contribution. Above, the two descriptions differ and the two gluon exchange cross-section exhibits a characteristic node which comes from the interference between the two graphs depicted in Fig. 1a. In the framework of the specific model discussed in this study this occurs around $-t = 2 \div 3 (GeV/c)^2$, but this is expected to survive in any reasonable model.

The physical reason is the following. Around $-t = 1 (GeV/c)^2$, the size of the interaction volume is about $0.2 fm$ and is comparable to the gluon correlation length : the distance over which a gluon can propagate (within which it is confined). The more likely mechanism is therefore the mechanism where one strange quark of the ϕ and one valence quark of the proton are close enough to be able to exchange two gluons. This does not mean that all the five quarks are in the small interaction volume, but only two. When the momentum transfer increases, components of small spatial extension are selected in the ϕ wave function, since in this exclusive process we require the proton to stay intact. The strange quarks of the ϕ can now both be at the same time in the interaction volume, and each of the exchanged gluon can couple to a different strange quark. At large t , this diagram overwhelms the diagram where the two gluons couple to the same strange quark. At intermediate t , both diagram interfere, providing us with an interesting signature of two gluon exchange mechanisms. Although non leading diagrams, such as those which imply a possible strange intrinsic component in the proton ground state, may shift or partially fill in this dip, its experimental observation would be particularly rewarding.

In the kinematical domain where these two gluon exchange mechanisms are relevant, they provide us with an opportunity to open up an almost virgin field : the study of quark correlations in hadronic matter. At a large enough momentum transfer t , each gluon can also couple to a different quark in the target ground state. On the one hand, this new mechanism is sensitive to the correlation between quarks in the proton wave function. On the other hand, it provides us with a way to reveal and to study possible hidden color components in the wave function of few body systems.

All these issues have been presented and discussed in lectures [18] and conference talks [19], where the various steps in the evolution of the problem can be traced back. They are at the basis of two experimental proposals : the first [20] at the Continuous Electron Beam Facility (CEBAF) and the second [21] at the European Laboratory For Electrons (ELFE) which is currently under discussion [22]. This paper is an attempt to adapt, to vector meson photoproduction at intermediate energies but high momentum transfer, methods which have been shown to successfully model non perturbative aspects of reactions induced at higher energy but low momentum transfer. This is the goal of the next section, where the corresponding models are reviewed and where the free parameters are extracted from related channels. Section 3 compares the predictions of the model to the sparse available data and put

a special emphasis on experiments which should be performed with the new generation of high intensity and high duty factor electron accelerators. Section 4 deals with applications to the nuclear case. Appendices gather more technical topics : relationships between cross-sections and amplitudes, between real and virtual photon absorption cross-sections, decay density matrix, derivation of the Pomeron and the two gluon exchange matrix elements,...

2 A model for vector meson photoproduction

2.1 Production of vector mesons at low t .

At low momentum transfer ($-t \leq 0.4 \text{ (GeV/c)}^2$), the cross section of the $\gamma p \rightarrow Vp$ reaction ($V = \rho, \phi$) is purely diffractive and takes the form [15,16] :

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt} \right)_{t=0} \exp(Bt) \quad (1)$$

In ϕ production, for instance, the variation with the incoming photon energy of the forward angle ($t = 0$) cross section exhibits a characteristic threshold behavior at low energy and becomes almost constant above $E_\gamma = 6 \text{ GeV}$. A very good fit is obtained with the following expression :

$$\left(\frac{d\sigma}{dt} \right)_{t=0} = C_\phi \left(\frac{p_\phi}{k} \right)_{CM}^2 \quad (2)$$

with $C_\phi = 2.93 \pm 0.08 \mu\text{b}/\text{GeV}^2$.

When the photon energy is large enough ($E_\gamma \geq 5 \text{ GeV}$) to avoid trivial threshold behavior, the cross section exhibits a universal momentum dependence and a change of slope around $-t = 0.4(\text{GeV/c})^2$: below $-t = 0.4(\text{GeV/c})^2$ the slope parameter takes the value $B_\phi = 6 \pm 0.5(\text{GeV/c})^{-2}$, and $B_\phi \simeq 4(\text{GeV/c})^{-2}$ above.

In ρ production, the cross-section exhibits a flat behavior above $E_\gamma = 3 \text{ GeV}$, and the slope parameter is $B_\rho \simeq 7(\text{GeV/c})^{-2}$ below $-t = 0.4(\text{GeV/c})^2$.

Above $-t = 1(\text{GeV/c})^2$, the experimental data set is very meagre. Some sparse results exist for ρ photoproduction [13] and there is no data at all for ϕ photoproduction at large t .

However, theoretical predictions are available.

2.2 The Pomeron model

The first one, proposed by Donnachie and Landshoff [2], is based on the Pomeron-photon analogy. Experiments suggest that the Pomeron couples to a quark like an isoscalar photon. However, they noticed that the Pomeron-quark coupling is not always point like. Indeed, when either one or both of the two quark legs in the Pomeron-quark-quark vertex goes far off-shell, the coupling decreases. They introduced phenomenologically a momentum scale μ_0 in order to reduce the coupling. Their ansatz is to consider a factor $\mu_0^2/(\mu_0^2 + m_q^2 - k^2)$ for each quark leg with four momentum k . In this model the cross-section for vector meson photoproduction takes the form (see Appendix B) :

$$\frac{d\sigma}{dt} = \frac{81m_V^3\beta_0^4\mu_0^4\Gamma_{e+e-}}{\pi\alpha_{em}} \left(\frac{s}{s_0}\right)^{2\alpha(t)-2} \left[\frac{F_1(t)}{(Q^2 + m_V^2 - t)(2\mu_0^2 + Q^2 + m_V^2 - t)} \right]^2 \quad (3)$$

where Q^2 , s and t are respectively the squared mass of the virtual photon, the total squared energy in the c.m. system and the four-momentum transfer between the incoming photon and the outgoing vector meson. The mass and the radiative decay width of the vector meson are respectively m_V and Γ_{e+e-} . The electromagnetic coupling constant is α_{em} and the proton isoscalar form factor is $F_1(t)$:

$$F_1(t) = \frac{4m_p^2 - 2.8t}{(4m_p^2 - t)(1 - t/0.7)^2} \quad (4)$$

The strength $\beta_0^2 = 4\text{GeV}^{-2}$ is fixed by the analysis [23] of the asymptotic behavior of the nucleon-nucleon scattering amplitude, in terms of Pomeron exchange. The Pomeron Regge trajectory is taken [23] from pp and $p\bar{p}$ data :

$$\alpha(t) = 1 + \epsilon' + \alpha't, \quad (5)$$

with $\alpha' = 0.25 (\text{GeV}/c)^{-2}$ and $\epsilon' = 0.08$, while $s_0 = 1/\alpha' = 4 (\text{GeV}/c)^2$. This simple model leads to a good agreement [2] with the EMC data concerning ρ production (Fig. 3), provided that $\mu_0^2 = 1.1\text{GeV}^2$.

2.3 The two gluon exchange model

The second attempt is also due to Donnachie and Landshoff [6]. They model vector meson photoproduction via an explicit calculation of the dominant mechanism at large value of the momentum transfer. When, say Q^2 or $-t > 1 (\text{GeV}/c)^2$, Pomeron exchange reduces to a simple two gluon exchange, i.e., the whole non perturbative process has no time to develop. Landshoff and Nachtmann have calculated [7] this contribution to quark-quark scattering, in the limit of high photon energy ($\nu \rightarrow \infty$) and assuming abelian gluons.

The cross-section for vector meson photoproduction is [6,7,9] :

$$\frac{d\sigma}{dt} = \frac{81m_V^3\Gamma_{e^+e^-}}{256\pi^3\alpha_{em}} [F_1(t)]^2 \left[\sqrt{\frac{\alpha_s(\Sigma^2)}{\alpha_n}} \int dl^2 \frac{-4l^2 + t}{(m_V^2 + Q^2 - 4l^2)(m_V^2 + Q^2 - t)} \left[4\pi\alpha_n D(l^2 + \frac{1}{4}t) \right]^2 \right]^2 \quad (6)$$

It is made of three parts (See Appendix B for details). The first part is a constant factor which depends on the various coupling constants and on the static properties of the vector meson. The second is the proton isoscalar form factor $F_1(t)$ which insures that the outgoing proton remains in its ground state. The third is the integral, over the transverse momentum, which describes the exchange of two gluons. The two terms which appear in the denominator correspond to the propagators of the far off-shell quarks marked by a circle in each graph of Fig. 1. In Eq. 6, their amplitudes have been combined in a compact expression.

When performing the loop integral, it happens that the exchanged gluons become on-shell. This induces infrared singularities which are unphysical since the gluons are confined and cannot propagate far away. Their propagator $D(l^2)$ must be regularized at low momentum, and is chosen as :

$$\alpha_n D(l^2) = \frac{\beta_0}{\sqrt{\pi}\lambda_0} \exp\left(-\frac{l^2}{\lambda_0^2}\right) , \quad l^2 \leq 0 \quad (7)$$

where α_n is the non-perturbative quark-gluon coupling (taken from [9] as $\alpha_n \simeq 0.3$) and β_0 is the phenomenological Pomeron-nucleon coupling. This regularization procedure introduces a momentum scale λ_0 and consequently a gluon correlation length ($a \simeq 1/\lambda_0$), a distance beyond which the gluon cannot propagate.

The factor $\alpha_s(\Sigma^2)/\alpha_n$ in Eq. 6 stands for the fact that the quark marked with a circle in Fig. 1 is far off-shell. The strong running coupling constant α_s should be used, instead of the effective coupling constant, at the corresponding quark-gluon vertex. Its argument Σ^2 is the degree of off-shellness of the quark and is defined in Appendix B.

Donnachie and Landshoff [6], and then Cudell [9], showed an analogy between the phenomenological Pomeron and the two gluon exchange approaches. Obviously, since it is a perturbative like calculation, there is no Regge factor in the two gluon result. When this Regge factor is removed from the Pomeron exchange amplitude, the similarity between the two cross-sections is striking when the loop integral in Eq. 6 is performed in an approximate way [9]. If the squared mass Q^2 of the virtual photon, or the mass m_V of the vector meson is large enough, one may neglect the dependence against l^2 in the denominator of the integrand of Eq. 6, and the cross

section takes the simple form :

$$\frac{d\sigma}{dt} = \frac{81m_V^3\beta_0^4\Gamma_{e^+e^-}}{4\pi\alpha_{em}} [F_1(t)]^2 \left[\sqrt{\frac{\alpha_s(\Sigma^2)}{\alpha_n}} \frac{2\lambda_0^2 + t}{(m_V^2 + Q^2 + 2\lambda_0^2)(m_V^2 + Q^2 - t)} \exp\left(\frac{t}{2\lambda_0^2}\right) \right]^2 \quad (8)$$

At $t = 0$, and in the limit $\alpha_s/\alpha_n \rightarrow 1$, this cross-section coincides with the Pomeron exchange cross-section (Eq. 3), provided that λ_0 is identified with μ_0 . Thus, in this limit, the two approaches are almost identical for low values of t , and the second graph in Fig. 1a acts as the form-factor at the quark-Pomeron vertex.

Eq. 8 shows explicitly that the cross-section exhibits a dip at $t = -2\lambda_0^2$. As we have already mentioned, this dip results from the cancellation between the direct two gluon exchange graph (Fig. 1a), where the two gluons couple to the same quark in the vector meson, and the crossed graph where each gluon couples to a different quark. This behavior also remains in the complete expression of the cross-section (Eq. 6). However, the dip occurs at a smaller value of $-t$, namely $-t \approx \lambda_0^2$ as we shall see later, at least in the range of Q^2 accessible to current experiments. We have checked that Eq. 8 becomes a decent approximation of Eq. 6 only above $Q^2 \simeq 20(GeV/c)^2$, or in the charmed quark sector.

All the numerical results shown in this study have been obtained by performing explicitly the integral in Eq. 6 and not using Eq. 8.

2.4 The contribution of the perturbative part of the gluon propagator

So far, we have used the regularized form (Eq. 7) of the gluon propagator. It accounts for the dressing of the gluon propagator and may be related to the size of the gluon condensate (see Appendix C). While this regularization is mandatory to deal with infrared divergencies and to parameterize non perturbative effects on the gluon propagator at low momentum, this is certainly not correct at high momentum. When the gluon momentum k goes to infinity, the propagator goes to zero as $1/k^2$ and not exponentially. A better approximation would be to attach a perturbative tail to the regularized gluon propagator :

$$\begin{aligned} \alpha_n D(l^2) &= \frac{\beta_0}{\sqrt{\pi}\lambda_0} \exp\left(\frac{l^2}{\lambda_0^2}\right) & , -l^2 \leq \kappa^2 \\ \alpha_n D(l^2) &= \frac{\alpha_n}{-l^2} & , -l^2 \geq \kappa^2 \end{aligned} \quad (9)$$

where κ is some momentum scale of the order of 1 GeV.

We have checked, by numerical integration of Eq. 6 and using Eq. 9, that the non perturbative tail of the gluon propagator does not change significantly (less than a few percent) the results presented in this paper.

In the kinematics considered in this work, the cross-sections are dominated by the non perturbative part of the gluon propagator. The two gluon exchange model provides us with a way to extend a perturbative like calculation to the non-perturbative regime.

3 Comparison with experiments

3.1 The Q^2 dependence of ρ leptonproduction

When integrated against t , the two gluon cross-section leads to a fair agreement with both the magnitude and the Q^2 dependence of the cross section of the $p(e, e')\rho p$ reaction [11] and of the cross section of the $p(\mu, \mu')\rho p$ reaction [12]. Fig. 3 shows the result which we get for the two gluon exchange cross-section (Eq. 6) when $\lambda_0^2 = 2.7 (GeV/c)^2$, together with the Pomeron exchange cross-section (Eq. 3) when $\mu_0^2 = 1.1 (GeV/c)^2$. While we have been able to reproduce the Pomeron result of Donnachie and Landshoff [2], we have not been able to reproduce the two gluon exchange result of Cudell [9]. This is apparent in Fig. 4 where our predictions for $\lambda_0^2 = 1.2$ and $2.7 (GeV/c)^2$ are compared to experiment.

Cudell decided to include the Regge factor $(s/s_0)^{2\alpha(t)-2}$ by hand in the two gluon amplitude. He found [9] that the value needed to fit EMC data is $\lambda_0^2 = 1.2 \pm 0.5 (GeV/c)^2$, in good agreement with the value $\mu_0 = 1.1 (GeV/c)^2$ needed if the Pomeron exchange cross-section had been used [2]. For this value of λ_0 , our result misses the data and the Cudell result by a factor two, even if we take into account the Regge factor. It should be noted that the expression of the two gluon cross-section quoted by Cudell [9] differs, by a numerical factor, from our Eq. 6 which coincides with the expression quoted by Donnachie and Landshoff [6] and which reduces to the Pomeron exchange cross-section in the large Q^2 and low $-t$ limit. We are therefore confident in our result.

In the spirit of the perturbative like nature of the two gluon exchange model and since non perturbative effects are taken into account in modeling the gluon propagator, we use instead the model as crude as it comes from Eq. 6, i.e. without including the Regge trajectory. The integration is done numerically using Eq. 7 for the gluon propagator. Fig. 4 shows that larger values of the parameter λ_0 , ($\lambda_0^2 = 2.7 \pm 0.5 (GeV/c)^2$) seem to be favored. However, the present set of data is not accurate enough to decide whether or not the Regge trajectory should be included. The reason is that such an integrated cross-section is sensitive only to

small values of t ($-t \leq 1 \text{ GeV}^2$). Only new data at larger values of t would allow to address this issue. Consequently, we discard the Regge factor in the following discussion.

It is worthwhile to point out that this model solves a long standing puzzle : the apparent violation of s-Channel Helicity Conservation (SCHC) by EMC data. When analyzed in the framework of VDM (Eq. A.14), the Q^2 dependence of ρ leptonproduction (Fig. 5) is consistent with a vanishing Longitudinal cross-section ($R = \sigma_L/\sigma_T \simeq 0$), while the analysis of the ρ decay matrix elements requires a sizable ratio R which grows linearly with Q^2 . On the contrary, the two gluon exchange model predicts a Q^2 dependence of the cross-section steeper than VDM, while satisfying SCHC as VDM. It reproduces both the cross-section, depicted in Fig. 5, and the ρ meson decay distribution [9]. It predicts that Transverse photons produce Transverse vector mesons and that Longitudinal photons produces Longitudinal vector mesons.

3.2 Large t behavior of ρ photoproduction

The model provides us with a prediction for ρ photoproduction at large values of t . Some sparse data for 6 GeV photons exist [13]. In Fig. 6, we present these data together with the predictions of the model for $\lambda_0 = 2.7 \text{ (GeV/c)}^2$. We have explicitly neglected the effects due to the Regge trajectory. If this factor were included, the cross-section would have been strongly suppressed for values of $-t$ larger than 2 (GeV/c)^2 .

Comparison with data looks correct for low values of t . The slope and the magnitude of the data are reproduced. For larger values of t , the model underestimates the data, although it comes closer to the data when large values of λ_0^2 are used.

However, it should be pointed out that at large t a competitive mechanism appears : quark interchange between ρ and the nucleon are likely to occur in this energy range. The corresponding cross-section is expected to scale as s^{-7} . As can be seen in Fig. 7, the sparse experimental data follow this scaling law in the range $5 \leq s \leq 12 \text{ GeV}^2$ (i.e. $2.8 \leq \nu \leq 6 \text{ GeV}$), around $-t \simeq 3 \div 4 \text{ (GeV/c)}^2$, where the angular distribution [13,24] exhibits a flat behavior. The cross-section for the two gluon exchange mechanism is almost independent of the incoming photon energy and is also plotted in Fig. 7. If this picture is correct, quark interchange mechanisms will dominate below $\nu \simeq 6 \text{ GeV}$ and will be expected to interfere with the two gluon exchange mechanism around $\nu \simeq 6 \div 10 \text{ GeV}$. A precise determination of the ρ meson photoproduction, in that energy and momentum transfer range, would certainly be rewarding in this respect.

Finally, it should be noted that the rise of the cross-section at the highest values of t , in Fig. 6, comes from the exchange of the nucleon in the u channel.

3.3 ϕ photo- and electro-production

Production of ϕ on nucleon has a big advantage when compared to ρ production. Since the ϕ is mainly made of a $s\bar{s}$ pair, quark interchange between ϕ and nucleon is highly suppressed. Furthermore, since the ϕ -nucleon coupling is small, the nucleon exchange in the u channel is suppressed. At large t , ϕ photoproduction is expected to be a much cleaner test for the two gluon exchange model.

Unfortunately, no data exist for ϕ production at $-t > 1$ (GeV/c)². The only available experimental data corresponds to low values of t : Ref. [25] for virtual photons and Refs. [14,15,16,17] for real photons.

Fig. 8 shows the t behavior of the cross-section at $Q^2 = 0$ and $Q^2 = 1$ (GeV/c)². The curves correspond to the prediction of two gluon exchange calculation (Eq. 6), changing ρ to ϕ parameters (mass and radiative decay width). We observe that the value of $\lambda_0^2 = 2.7$ GeV² leads to an impressive agreement with experiment, around $-t \simeq 1$ (GeV/c)² down to $-t \simeq 0.5$ (GeV/c)². Below the model is not expected to be correct. A value of $\lambda_0^2 = 1.2$ GeV² is ruled out by experiment. The Q^2 dependence of the data is also very well reproduced. This can be seen in Fig. 9, where we display the experimental results for a momentum transfer around $-t \approx 1$ GeV² and the model calculation with $\lambda_0^2 = 2.7$ GeV². In this low t range, the cross-sections are not sensitive to the inclusion of the Regge factor.

The Pomeron contribution is also shown in Fig.8 and agrees perfectly well with the data. It is remarkable that the two extreme ways of modeling the Pomeron (phenomenological Pomeron or two gluon description) provide us with a satisfactory description of both the magnitude and momentum dependence of the existing cross-sections of vector meson production in the light quark sector as well as in the strange quark sector. However, they do differ at larger $-t$.

The large t dependence of the cross-section has already been shown in Fig. 2. As already stated, the dip around $t \simeq 2 \div 3$ (GeV)² comes from the interference between the two graphs in Fig. 1. Their individual contributions are separately shown in Fig. 10. Experimental determination of such an interference would be a clear indication of the relevance of the two gluon model. However, due to the smallness of the cross-section, such a measurement is impossible with the present generation of high energy electron accelerators or with existing low intensity lepton beams. It definitively calls for a new generation of intense continuous electron beams. Such an experiment is a part of the research program of the ELFE project presently under discussion [22]. In the meantime, it will be run at CEBAF [20], and although the $(4 \div 6$ GeV) energy range might still be too low, this will be a good opportunity to see the onset of the two gluon exchange mechanisms.

3.4 J/Ψ photoproduction

Due to the large value of the charmed quark mass, the two gluon exchange model of J/Ψ electroproduction is expected to make sense at lower values of $-t$ and Q^2 than those required in ρ or ϕ production channels. It should be valid for low $-t$ even at the real photon point, but at higher energy to avoid trivial threshold behavior and to fulfill our high energy approximation.

When the mass of the J/ψ and its radiative decay constant are used, the two gluon exchange model reproduces (Fig. 11) the slope of the experimental $-t$ distribution [26] at $\nu = 150 \text{ GeV}$, with $\lambda_0^2 = 2.7 \text{ GeV}^2$. As in the case of ϕ production, it is very close to the prediction of the Pomeron exchange model for $\mu_0^2 = 1.2 \text{ GeV}^2$, while it exhibits a too steep t dependence when $\lambda_0^2 = 1.2 \text{ GeV}^2$ is used.

However, both the Pomeron and the two gluon exchange models overestimate the experiment by about an order of magnitude. This comes from the fact that the coupling of the Pomeron to a charmed quark is weaker than its coupling to a light or a strange quark. The way to account for such a different coupling consists in replacing β_0^4 by $\beta_0^2\beta_c^2$ in Eqs. 3 and 6, where β_c^2 now stands for the phenomenological coupling between the Pomeron and the charmed quark. The value $\beta_c^2 = 0.8 \text{ GeV}^2$ leads to a perfect agreement between the Pomeron cross-section and experiment (Fig. 12), and a fair agreement between the two gluon cross-section and experiment. A value of $\beta_c^2 = 0.4 \text{ GeV}^2$, however, is preferred by the two gluon exchange model.

It should be noted that, in the charmed quark sector, Eq. 8 becomes a good approximation to Eq. 6 and reduces to the Pomeron exchange cross-section for $\lambda_0 = \mu_0$, but only at $t = 0$ (see Fig. 11). The two cross-sections, however, exhibit a different t dependence. Also, the node in the two gluon cross-section (Fig. 12) occurs at a value of $-t$ very close to $2\lambda_0^2$, contrary to the light quark case.

3.5 Prospects and discussion

The two gluon exchange mechanism appears to be a good candidate to explain, with the same set of parameters, the dependency against Q^2 of the integrated cross-section of ρ electroproduction at large energy, as well as the dependency against t and Q^2 of the ϕ photo and electroproduction at lower energy and around $-t \simeq 1(\text{GeV}/c)^2$. There, it matches the prediction of the Pomeron exchange model. Obviously, the determination of the behavior of the ϕ production cross-section at higher values of the momentum transfer t , and more specifically the observation of the dip, would be a more stringent test of the model. The variation of the position of the dip with the incoming photon energy ν or four-momentum Q^2 , would be a hint of other mechanisms or of the breakdown of the approximations which have been made in deriving Eq. 6.

For instance, the high energy limit, in which the two gluon exchange amplitude has been derived, is certainly valid in the energy range of the CERN experiment, or of the experiment planned at ELFE, but may be questionable in the range $\nu \simeq 4 \div 8 \text{ GeV}$ where most of the data exist. The corresponding corrections should be investigated, but they lie outside the exploratory scope of this article.

Possible intrinsic strange component in the nucleon ground state may alter the simple and elegant behavior of two gluon exchange processes. However, the corresponding mechanisms involve higher order components in the Fock expansion of the proton wave function, whose contributions to the cross-section are suppressed in high momentum transfer exclusive reactions. Intrinsic strange components may more likely be revealed in the $p(e, e'\phi)p$ reaction at $-t \leq 1(\text{GeV}/c)^2$, through interference with the dominant diffractive scattering of the ϕ . Spin observables, and more particularly the spin density matrix of the decay of the vector meson, would certainly be useful in revealing these interferences.

Such a correction is expected to be much weaker in $J\Psi$ production, since the intrinsic charm component of the nucleon wave function is probably much smaller than its strange component. Moreover, due to the large value of the charmed quark mass, the two gluon model is expected to be valid at lower momentum transfer ($-t$ or Q^2) than for ϕ or ρ meson production. The comparison of J/ψ production, with the production of those lighter mesons, will be rewarding in this respect. It should however be noted that the high energy approximation, which has been made in deriving Eq. 6 is valid at higher energy in J/Ψ production than in ϕ production. Also, the J/Ψ production cross-section is lower than for the ϕ , and may make for a more difficult determination of its behavior at large t .

Finally, the comparison between ϕ and ρ production will also be rewarding. In the latter case quark interchange mechanisms may compete with two gluon exchange at low energy, let say below $\nu \sim 10 \text{ GeV}$.

All these issues are open and deserve further dedicated studies on the theoretical as well as on the experimental side.

4 The nuclear case

If this two gluon exchange mechanism is confirmed by further experiments, it will provide us with a powerful way to study the short range behavior of nuclear matter—more specifically possible hidden color components. Alternatively, the nuclear environment may be used as a filter which modifies the shape of the elementary two gluon amplitude or the relative importance of other processes, such as, for instance, quark interchange or rearrangement.

4.1 Hidden color components in few body systems

When the nucleon is embedded in the nuclear medium, two mechanisms govern the photo- and the electroproduction of ϕ mesons. The first is trivial : it is the quasi-free production mechanism. The second is much more interesting. It is the exchange of two gluons, each of them coupled to a quark belonging to a different nucleon (Fig. 13a). Since the coupling of a single gluon to a quark changes its color, two gluon exchange provides us with a way to look for hidden color components, or more generally for the correlation between two quarks in hadronic matter. A coincidence experiment, for instance $D(\gamma, \phi p)n$ or ${}^3\text{He}(\gamma, \phi 2p)n$, must be performed to disentangle them.

The cross section of the quasi-free process in the $D(\gamma, \phi p)n$ reaction takes the form [27] :

$$\frac{d\sigma}{dtd\vec{n}} = (1 + \beta_n \cos \theta_n) \left. \frac{d\sigma}{dt} \right|_{\gamma p \rightarrow \phi p} \rho(|\vec{n}|) \quad (10)$$

where $|\vec{n}|$, θ_n and β_n are respectively the momentum, the polar angle and the velocity of the spectator neutron, and where $\rho(|\vec{n}|)$ is nothing but the nucleon momentum distribution in deuterium. When integrated against the angles of the spectator neutron, this expression reduces to :

$$\frac{d\sigma}{dtd|\vec{n}|} = \left. \frac{d\sigma}{dt} \right|_{\gamma p \rightarrow \phi p} 4\pi \vec{n}^2 \rho(|\vec{n}|) \quad (11)$$

with $\int \rho(|\vec{n}|) d\vec{n} = 1$.

It decreases very quickly [27] as the undetected neutron momentum increases. Consequently, selecting high values of neutron momentum is the way to suppress the contribution from such a trivial mechanism. The quasi-free contribution in Fig. 14 has been computed with the Paris wave function [28] of the deuterium.

The cross section corresponding to the exchange of each of the two gluons with a different quark cluster is expected to exhibit a flatter momentum distribution, since the recoil momentum is shared between the two nucleons. However it is very difficult to make a reliable quantitative estimate of its magnitude.

A first, rough, approach would be to write the corresponding cross section as :

$$\frac{d\sigma}{dtd|\vec{n}|} = \left. \frac{d\sigma}{dt} \right|_{\gamma p \rightarrow \phi p} 4\pi \vec{n}^2 \left[\varphi_{cc}\left(\frac{\vec{n}}{2}\right) \right]^2 \frac{F_1^4(\frac{t}{4})}{F_1^2(t)} \quad (12)$$

where the fourth power of the nucleon form factor comes from the fact that two nucleons have to recombine, each at the momentum transfer $t/4$. It is assumed that the form factor of the transition between a colored cluster and the nucleon does not differ too much from the nucleon form factor. The ratio of the nucleon form

factors acts as an enhancement factor $\simeq 7$ at $-t = 1 \text{ GeV}^2$, for example. It is also assumed that the recoil momentum is equally shared between the two colored clusters whose wave function is $\varphi_{cc}(\frac{\vec{n}}{2})$. This component of the deuterium wave function is unknown, and only few predictions are available. As an example and to set the order of magnitude, the hidden color contribution in Fig. 14 has been obtained by using the Fourier transform of the wave function depicted in Fig. 11 of Ref. [30]. Since it exhibits a node around 500 MeV/c, a node appears in the cross-section around $n \simeq 1 \text{ GeV/c}$. This is unphysical, since in a more elaborate calculation the integration against the nucleon internal momentum washes it out. Anyway, this rough estimate shows that the hidden color component contribution dominates the cross-section above 1 GeV/c. The calculation reported in [30] predicts a probability of finding a hidden color component in the deuterium wave function of the order of 0.1%. Fig. 14 also shows what one may expect for a probability around 1%.

A more educated guess would be to introduce the relative wave function of two quarks $\varphi_{qq}(l^2, \vec{n})$ in Eq. 6 :

$$\frac{d\sigma}{dt d\vec{n}} \propto \left| F_1^2\left(\frac{t}{4}\right) \int dl^2 \varphi_{qq}(l^2, \vec{n}) \frac{-4l^2 + t}{(m_\phi^2 + Q^2 - 4l^2)(m_\phi^2 + Q^2 - t)} \left[D(l^2 + \frac{1}{4}t) \right]^2 \right|^2 \quad (13)$$

But again this wave function is not known and more work should be done, both on the theoretical and on the experimental sides to determine it, or at least to put some constraints on it. From Eq. 13, one may infer that the interference between the two graphs in Fig. 1 still remains, but that the corresponding dip in the t distribution will be shifted in a nucleus, contrary to Eq. 12, which predicts that the dip is located at the same place as in the free nucleon case. A study of the variation of the cross-section, not only against $|\vec{n}|$, but also against t and Q^2 will be rewarding.

In order to increase the probability of the hidden color component, or to enhance the effect of correlations between quarks, one would like to increase the density of the target nucleus. The reactions ${}^3\text{He}(\gamma, \phi 2p)n$ and ${}^4\text{He}(\gamma, \phi 2p)nn$ are good candidates. A further advantage comes from the fact that the target pp pair is almost in a pure 1S_0 state (see for instance [29]), contrary to the deuterium which has a sizable D wave component. The high momentum tail of the quasi-free process is reduced accordingly, leaving more room for two gluon exchange quark rearrangement processes.

However, the contribution from higher order processes, like ϕ -nucleon rescattering for instance, should be estimated before making definite statements. This can be done with the methods which have been already used in the successful analysis of pion electroproduction on few-body system [27]. The corresponding study will be reported in another publication.

4.2 ρ production in nuclei

When a ρ meson is produced in a nucleus, the relative importance of two gluon exchange and quark interchange mechanisms may be different from the free nucleon case. Possible interferences between their amplitudes may exhibit a different pattern in each case. Although this issue opens up a new field, the theory is almost in its infancy and hints should be given by new experiments. For instance, the comparison between ρ and ϕ meson production channels in nuclei above $\nu = 10 \text{ GeV}$, where, according to Fig. 7, quark interchange mechanisms appear to be suppressed, and then around $\nu \simeq 6 \div 8 \text{ GeV}$, where interferences are expected to be greatest, could be rewarding. However, higher order nuclear effects may be again important and make the analysis difficult. These issues deserve dedicated studies.

5 Conclusion

At large momentum transfer, exclusive photo- and electroproduction of vector mesons appear to be a promising field which is still almost unexplored.

In the light quark sector, quark interchange mechanisms are very likely to dominate the cross-section. Their contribution is strongly decreasing at high energy, where two gluon exchange mechanisms take over and reproduce the sparse available data.

In the strange quark sector, quark interchange mechanisms are strongly suppressed, provided that no sizable intrinsic strange component exists in the nucleon. The two gluon exchange mechanism is therefore expected to drive the cross-section, even at energies as low as $5 \div 6 \text{ GeV}$, but large momentum transfer.

Such a two gluon exchange mechanism provides us with a representation of the hard part of the Pomeron. At high momentum transfer, the two active quarks, in the vector meson and the nucleon, are close enough to prevent the full evolution of non perturbative processes which build up the Pomeron. This is one of the way of studying the Pomeron structure.

In nuclei, it provides us with a way to unravel the short range structure of hadronic matter. Each of the two exchanged gluons may couple to a quark belonging to a different nucleon in the target. Such a mechanism would certainly be sensitive to quark correlations, and more particularly to hidden color components.

This paper is a review of the status of our present understanding of two gluon exchange mechanisms and of their potential use in the study of hadronic matter at short distances. We have investigated several research axes which deserve more thorough dedicated studies. More particularly, new experiments are mandatory in

order to reveal the salient features of this open field. While they require energies around 15 GeV , they can be started at lower energies.

Appendices

A Cross-sections

The cross-section of the $p(e, e'V)p$ reaction, followed by the decay of the vector meson into two scalar mesons ($\rho \rightarrow \pi^+\pi^-$ or $\phi \rightarrow K^+K^-$), is related to the cross-section of the virtual photon reaction $p(\gamma_\nu, V)p$ as follows :

$$\frac{d\sigma}{dEd\cos\theta_e d\Phi_e dt d\Omega^*} = \Gamma_\nu \frac{d\sigma}{d\Phi_e dt d\Omega^*} \quad (\text{A.1})$$

where the flux of the virtual photons is :

$$\Gamma_\nu = \frac{\alpha_{em}}{2\pi^2} \frac{E'}{E} \frac{|\vec{k}|}{1-\epsilon} \frac{1}{-q^2} \quad (\text{A.2})$$

The polarization of the virtual photon is :

$$\epsilon = \left[1 - 2 \frac{\vec{k}^2}{q^2} \tan^2 \frac{\Theta_e}{2} \right]^{-1} \quad (\text{A.3})$$

The energy of the incident electron is E , while the energy and the angles of the scattered electron are respectively E' , Θ_e and Φ_e (as measured with respect to the vector meson emission plane). The energy, the momentum and the squared mass of the virtual photon are respectively ν , $\vec{k}$ and $q^2 = -Q^2$. The solid angle Ω^* of the final scalar mesons is defined in the rest frame of the vector meson.

The virtual photon absorption cross-section can be written in terms of the vector meson decay angular distribution as [25,31] :

$$\frac{d\sigma}{d\Phi_e dt d\Omega^*} = \frac{d\sigma}{d\Phi_e dt} W(\theta, \phi, \Phi_e) \quad (\text{A.4})$$

where θ and ϕ are respectively the decay polar and azimuthal angles measured in the vector meson c.m. frame. The models considered in this study conserve helicity in the s -channel and involve natural parity exchange, in which case the decay angular distribution can be cast in the form [31] :

$$W(\theta, \phi, \Phi_e) = \frac{3}{8\pi} \left(\frac{1}{1+\epsilon R} \right) \left[(1 + \epsilon R \cos 2\psi) \sin^2 \theta + 2\epsilon R \cos^2 \theta - \sqrt{2\epsilon R(1+\epsilon)} \cos \psi \cos \delta \sin 2\theta \right] \quad (\text{A.5})$$

where $\psi = \Phi_e + \phi$ and δ is the phase between the two helicity conserving amplitudes. The ratio between the longitudinal and the transverse cross-section is :

$$R = \frac{d\sigma_L/dt}{d\sigma_T/dt} \quad (\text{A.6})$$

For real photons $R = 0$, and the cross-section of the reaction $p(\gamma, \phi)p$ takes the form :

$$\frac{d\sigma}{dtd\Omega^*} = \frac{d\sigma_T}{dt} \frac{3}{8\pi} \sin^2 \theta \quad (\text{A.7})$$

When integrated against the decay azimuthal angle ϕ , Eq. A.5 reduces to :

$$\int d\phi W(\theta, \phi, \Phi_e) = \frac{3}{4} \left(\frac{1}{1 + \epsilon R} \right) [\sin^2 \theta + 2\epsilon R \cos^2 \theta] \quad (\text{A.8})$$

When integrated further against the decay polar angle, it reduces to unity :

$$\int d\phi d\cos \theta W(\theta, \phi, \Phi_e) = 1 \quad (\text{A.9})$$

and the vector meson electroproduction cross-section takes the familiar form [32]:

$$\frac{d\sigma}{dtd\Phi_e} = \frac{d}{2\pi dt} \left[\sigma_T + \epsilon\sigma_L + \epsilon \cos 2\Phi_e \sigma_{TT} - \sqrt{\frac{-q^2\epsilon(\epsilon+1)}{2\nu^2}} \cos \Phi_e \sigma_{TL} \right] \quad (\text{A.10})$$

When integrated against the electron azimuthal angle Eq. A.10 reduces to :

$$\frac{d\sigma}{dt} = \frac{d}{dt} [\sigma_T + \epsilon\sigma_L] \quad (\text{A.11})$$

The Transverse and Longitudinal cross-sections are related to the matrix elements in the following way :

$$\begin{aligned} \frac{d\sigma_T}{dt} &= \frac{\alpha_{em}}{4s^2} \frac{1}{2} \left[\sum |M_X|^2 + \sum |M_Y|^2 \right] \\ \frac{d\sigma_L}{dt} &= \frac{\alpha_{em}}{4s^2} \frac{Q^2}{\nu^2} \sum |M_Z|^2 \end{aligned} \quad (\text{A.12})$$

where the averaging over the magnetic quantum numbers of the target proton and the summation over those of the outgoing proton are implicitly understood, and where M_X , M_Y and M_Z are the projections of the hadronic matrix element on the three cartesian axis.

Finally, when only integrated against the two azimuthal angles ϕ and Φ_e , the vector meson electrodisintegration cross-section takes the form :

$$\frac{d\sigma}{dtd\cos \theta} = \frac{d\sigma_T}{dt} \frac{3}{4} [\sin^2 \theta + 2\epsilon R \cos^2 \theta] \quad (\text{A.13})$$

In the framework of VDM, the momentum dependence of $d\sigma/dt$ is given by the vector meson propagator and one gets the formula which has been used for the analysis of EMC data [12] :

$$\left. \frac{d\sigma}{dtd\cos \theta} \right|_{VDM} = \frac{d\sigma_T(Q^2 = 0)}{dt} \left[\frac{m_V^2}{Q^2 + m_V^2} \right]^2 \frac{3}{4} [\sin^2 \theta + 2\epsilon R \cos^2 \theta] \quad (\text{A.14})$$

The analysis of the vector meson polar angular distribution allows the determination of the ratio of the Longitudinal to the Transverse virtual photon absorption cross-section, which is usually expressed as follows :

$$R = \frac{d\sigma_L/dt}{d\sigma_T/dt} = \xi^2 \frac{Q^2}{m_V^2} \quad (\text{A.15})$$

For instance, the analysis of the ρ decay distribution in the EMC data [12] requires $\xi^2 = 0.4$.

B The matrix elements

We give here a schematic derivation of the various matrix elements, with special emphasis on the approximations which have been made.

B.1 Pomeron exchange

The analysis [23] of nucleon-nucleon scattering at high energy leads to infer that the Pomeron couples to the valence quark as an isoscalar photon and that the corresponding quark-quark interaction is [2] :

$$\beta_0^2 \bar{u} \gamma_\mu u \bar{u} \gamma_\mu u \left(\frac{s}{s_0} \right)^{\alpha(t)-1} \exp \left[-i \frac{\pi}{2} (\alpha(t) - 1) \right] \quad (\text{B.1})$$

where $\beta_0^2 = 4 \text{ GeV}^{-2}$ and where the parameters of the Pomeron Regge trajectory $\alpha(t) = 1 + \epsilon' + \alpha' t$ are $\alpha' = 0.25 \text{ GeV}^{-2}$, $\epsilon' = 0.08$ and $s_0 = 1/\alpha' = 4 \text{ GeV}^2$. Within this model, the differential cross-section of elastic nucleon-nucleon scattering reduces to :

$$\frac{d\sigma}{dt} = \frac{1}{4\pi} [3\beta_0 F_1(t)]^4 \left(\frac{s}{s_0} \right)^{2\alpha(t)-2} \quad (\text{B.2})$$

where the factor 3 takes into account that three valence quarks must recombine into a nucleon, whose structure results in the isoscalar form factor :

$$F_1(t) = F_1^p(t) + F_1^n(t) = F_1^p(t) \quad (\text{B.3})$$

We assume $F_1^n(t) = 0$ in this work.

In the graph which describes the electroproduction of vector mesons (Fig. 15), the loop integral in the upper part, is computed assuming that the two quark legs, q and q_2 , which recombine into the vector meson, are almost on-shell and share equally the four-momentum of the vector meson ($q \simeq q_2 \simeq P_V/2$). The third quark leg q_1 , which is exchanged between the photon and the Pomeron, is far off-shell and its

propagator is factored out of the loop integral. The denominator of its propagator is :

$$\Sigma^2 = q_1^2 - m_q^2 = -\frac{1}{2}[Q^2 + m_V^2 - t] \quad (\text{B.4})$$

assuming that the quark mass is $m_q \simeq m_V/2$. After the integration in the quark loop, the vertex function of the vector meson, including the attached quark propagator, reduces to :

$$\frac{1}{2\sqrt{6}} \gamma \cdot \epsilon_V f_V (\gamma \cdot P_V + m_V) \quad (\text{B.5})$$

where ϵ_V and P_V are respectively the polarization vector and the four-momentum of the vector meson, and where its decay constant f_V is related to its radiative decay width Γ_{e+e-} as follows :

$$f_V^2 e_q^2 = \frac{3m_V}{8\pi\alpha_{em}^2} \Gamma_{e+e-} \quad (\text{B.6})$$

In the numerical estimates we have used the values of the radiative decay width given in ref. [33].

The lower part of the graph is nothing but the exchange of the Pomeron between a quark and a nucleon. According to Eq. B.2, the amplitude can be cast in the simple form :

$$[3F_1(t) \beta_0] s \left(\frac{s}{s_0} \right)^{\alpha(t)-1} \left[\frac{\mu_0^2}{-q_1^2 + m_q^2 + \mu_0^2} \beta^0 \right] \quad (\text{B.7})$$

It is made of three parts. The first is the effective coupling of the Pomeron to an isoscalar nucleon. The second is the Pomeron Regge trajectory. And the last factor is the effective coupling of the Pomeron to the off-shell quark q_1 (see section 2.2).

Gathering all these pieces together and performing the necessary trace evaluation lead to the amplitude [6] :

$$M = 3F_1(t) \frac{4\sqrt{6}m_V e_q f_V \beta_0^2 \mu_0^2}{(Q^2 + m_V^2 - t)(2\mu_0^2 + Q^2 + m_V^2 - t)} \epsilon \cdot \epsilon_V s \left(\frac{s}{s_0} \right)^{\alpha(t)-1} \quad (\text{B.8})$$

where ϵ is the photon polarization factor. When squared this amplitude leads to the cross-section given by Eq. 3.

B.2 Two gluon exchange

In the large energy limit ($\nu \rightarrow \infty$), the crossed two gluon exchange graph contribution cancels the real part of the direct two gluon exchange in quark-quark scattering (Fig. 16). Only the imaginary part of the direct exchange graph, where the two intermediate quarks are on-shell, survives. Considering only abelian gluons, Landshoff and Nachtmann [7] demonstrated that this contribution to the quark-quark scattering amplitude reduces to a form very similar to the Pomeron exchange amplitude

(Eq. B.1) :

$$\bar{u}\gamma_\mu u \bar{u}\gamma_\mu u \frac{1}{8\pi^2} \int d^2\vec{l} \left[4\pi\alpha_n D \left([\vec{l} + \frac{1}{2}\vec{q}_T]^2 \right) \right] \left[4\pi\alpha_n D \left([\vec{l} - \frac{1}{2}\vec{q}_T]^2 \right) \right] \quad (\text{B.9})$$

where $l^2 = -\vec{l}^2$ is the square of the transverse momentum of the exchanged gluon and $\vec{q}_T^2 = -t$. When an exponential form (Eq. 7) is used for the gluon propagator this amplitude reduces to :

$$\bar{u}\gamma_\mu u \bar{u}\gamma_\mu u \frac{1}{8\pi} \int dl^2 \left[4\pi\alpha_n D(l^2 + \frac{1}{4}t) \right]^2 \quad (\text{B.10})$$

When this two-gluon exchange amplitude is used, the nucleon-nucleon elastic scattering cross-section at $t = 0$ fixes the norm of the gluon propagator :

$$2\pi \int_{-\infty}^0 dl^2 \left[\alpha_n D(l^2) \right]^2 = \beta_0^2 \quad (\text{B.11})$$

The vector meson production amplitude, corresponding to the coupling of the two gluons to the same quark in Fig. 2, takes the form :

$$M = 3F_1(t) \frac{2\sqrt{6}m_V e_q f_V}{(Q^2 + m_V^2 - t)} s \epsilon \cdot \epsilon_V \sqrt{\frac{\alpha_s(\Sigma^2)}{\alpha_n}} \frac{1}{8\pi} \int dl^2 \left[4\pi\alpha_n D(l^2 + \frac{1}{4}t) \right]^2 \quad (\text{B.12})$$

where Σ^2 stands for the degree of off-shellness of the quark which connects the photon and one gluon, as given by Eq. B.4.

Using the norm condition (Eq. B.11), Eq. B.12 reduces to the Pomeron exchange amplitude (Eq. B.8), without the phenomenological form-factor $\mu_0^2/(\mu_0^2 + m_q^2 - q_1^2)$ at the quark-Pomeron vertex, in the limit $\frac{\alpha_s(\Sigma^2)}{\alpha_n} \rightarrow 1$.

In the graph where each gluon couples to a different quark of the vector meson, the denominator of the propagator of the far off-shell quark is :

$$-4l^2 + Q^2 + m_V^2 \quad (\text{B.13})$$

and the corresponding amplitude is :

$$M = -3F_1(t) 2\sqrt{6}m_V e_q f_V s \epsilon \cdot \epsilon_V \sqrt{\frac{\alpha_s(\Sigma^2)}{\alpha_n}} \frac{1}{8\pi} \int dl^2 \left[4\pi\alpha_n D(l^2 + \frac{1}{4}t) \right]^2 \frac{1}{(Q^2 + m_V^2 - 4l^2)} \quad (\text{B.14})$$

which combined with Eq. B.12 leads to :

$$M = 3F_1(t) 2\sqrt{6}m_V e_q f_V s \epsilon \cdot \epsilon_V \sqrt{\frac{\alpha_s(\Sigma^2)}{\alpha_n}} \frac{1}{8\pi} \int dl^2 \left[4\pi\alpha_n D(l^2 + \frac{1}{4}t) \right]^2 \left[\frac{1}{(Q^2 + m_V^2 - t)} - \frac{1}{(Q^2 + m_V^2 - 4l^2)} \right] \quad (\text{B.15})$$

and to the cross-section given by Eq. 8. As noted in Sect. 2.3, this second graph provides us with a more microscopic explanation of the phenomenological form factor which is used in the Pomeron exchange cross-section.

C The gluon condensate

The location of the dip in the t distribution of vector meson electroproduction depends on the value of the slope λ_0^2 of the gluon propagator, which in turn can be related to the size of the gluon condensate.

The relationship between the Pomeron structure and the gluon condensate M_c is, in fact, the starting point of the work of Landshoff and Nachtmann :

$$\langle 0 | g^2 G_{\mu\nu}^a(0) G^{a\mu\nu}(0) | 0 \rangle = M_c^4 \quad (\text{C.1})$$

When the gluon propagator considered in Eq. 7 is used, this takes the form [6] :

$$M_c^4 = \frac{3\beta_0\lambda_0^5}{\pi^{3/2}} \quad (\text{C.2})$$

With $\lambda_0^2 = 1.2 \text{ GeV}^2$ one gets $M_c = 1.04 \text{ GeV}$, which is of the order of the expected value [34]. If one makes the calculation with $\lambda_0^2 = 2.7 \text{ GeV}^2$, one gets $M_c = 1.74 \text{ GeV}$, a little bit too high but still consistent with the expected value.

The correlation length, or the size of the gluon condensate, is also related [6] to the slope parameter through :

$$a = \frac{(4\pi)^{\frac{1}{10}}}{\lambda_0} \quad (\text{C.3})$$

One gets $a = 0.29 \text{ fm}$ for $\lambda_0^2 = 1.2 \text{ GeV}^2$, and $a = 0.19 \text{ fm}$ for $\lambda_0^2 = 2.7 \text{ GeV}^2$.

However, there are many theoretical ambiguities about this calculation. First, there is an incoherence with the subtraction of divergencies. Indeed, in perturbation theory the left hand side of Eq. C.1 is ultraviolet divergent and the divergent part is subtracted. In the propagator used here, the perturbative part is subtracted off only at short distances. Secondly in the Landshoff and Nachtmann calculation,

gluons are abelian and all non perturbative effects are contained in the regularized gluons propagator. Thus, obtaining the correct result for the gluon condensate with a value of λ_0^2 which seems to be favored by ρ production data, may be nothing but a coincidence.

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Figure Captions.

Fig. 1: a) The two gluon exchange mechanisms which survive at high energy in vector meson photo- and electroproduction on free nucleon. b) The Pomeron exchange mechanism. The quarks marked with a circle are far off-shell.

Fig. 2: The cross section of the $\gamma p \rightarrow \phi p$ reaction at $\nu \simeq 10 \text{ GeV}$ plotted against t . The dashed line corresponds to the Pomeron exchange contribution (when $\mu_0^2 = 1.1 \text{ GeV}^2$). The full line corresponds to the two gluon exchange contribution (when $\lambda_0^2 = 2.7 \text{ GeV}^2$). The experimental cross-sections are taken from refs. [14,15, 16,17].

Fig. 3: The integrated cross-section of the $\gamma^* p \rightarrow p \rho$ as measured in the EMC experiment [12] is plotted against the squared mass of the virtual photon. The dashed curve corresponds to the Pomeron exchange model, while the full curve corresponds to the two gluon exchange model. The values of λ_0 and μ_0 are the same as in Fig.2.

Fig. 4: The contribution of the two gluon exchange model, in the same kinematics as in Fig.3, for different values of the slope parameter λ_0 of the gluon propagator. The dashed curves include the Regge trajectory factor, while the full curves do not.

Fig. 5: The contribution of σ_T (dashed curve) and $\sigma_T + \epsilon\sigma_L$ (full curve) to the cross-section of ρ leptonproduction in the same kinematic as in Fig. 4. In addition the prediction of VDM (dash-dotted line) is shown for a vanishing contribution of the longitudinal cross-section ($\xi^2 = 0$ in Eq. A.14).

Fig. 6: The angular distribution of the ρ meson emitted in the $p(\gamma, \rho)p$, at $\nu = 6 \text{ GeV}$, plotted against t . Data are from ref. [13]. The curve is the prediction of the two gluon exchange model for $\lambda_0^2 = 2.7 \text{ GeV}^2$.

Fig. 7: The ρ photoproduction cross-section at $t \approx 3 \div 4 \text{ (GeV/c)}^2$ is plotted against s (c.m. squared total energy). The solid line depicts the s^{-7} behavior predicted by quark interchange models. The two gluon exchange contribution is also shown (dashed line).

Fig. 8: The $p(e, e'\phi)p$ reaction cross-section plotted against t , at $Q^2 = 0$ (real photons) in a), and $Q^2 = 1(\text{GeV/c})^2$ in b). Data come from Cornell [25] for virtual photons, and are the same as in Fig. 2 for real photons. The dashed curve is the prediction of the Pomeron exchange model, while the dot-dashed and full curves correspond to the predictions of the two gluon exchange model for $\lambda_0^2 = 1.2$ and 2.7 GeV^2 respectively.

Fig. 9: The $p(e, e'\phi)p$ reaction cross-section against Q^2 at $-t = 1 \text{ (GeV/c)}^2$. Data comes from Cornell [25], and the curve is the prediction of the two gluon exchange model for $\lambda_0^2 = 2.7 \text{ GeV}^2$.

Fig. 10: The $p(\gamma, \phi)p$ reaction cross-section plotted against t . The contribution of each graph in Fig. 1 is shown separately : the two gluons couple to the same quark in the dashed line, while each of them couples to a different quark in the dot-dashed line. The full line corresponds to the full model.

Fig. 11: The cross-section of the $\gamma p \rightarrow pJ/\Psi$ reaction is plotted against t , when $\nu \simeq 150 \text{ GeV}$. The curves have the same meaning as in Fig. 8, and correspond to the same value $\beta_c^2 = \beta_0^2 = 4 \text{ GeV}^{-2}$ as in the light and strange quark sector. The data comes from ref. [26]

Fig. 12: The same as in Fig. 11, but for $\beta_c^2 = \frac{1}{5}\beta_0^2 = 0.8 \text{ GeV}^{-2}$.

Fig. 13: Hidden color graph (a) and quasi-free graph (b) in the $D(\gamma, p\phi)n$ reaction.

Fig. 14: Variations of the $D(\gamma, p\phi)n$ reaction cross-section against the recoil neutron momentum $|\vec{n}|$, at fixed $-t = 1 \text{ GeV}^2$. Solid line : quasi-free contribution. Dashed line : contribution of the hidden color component when its probability is 0.1 %. Dash-dotted curve : the same for a probability of 1%.

Fig. 15: Pomeron exchange graphs in exclusive vector meson photoproduction (a) and elastic nucleon-nucleon scattering (b).

Fig. 16: Direct (a) and crossed (b) two gluon exchange graphs in quark-quark scattering.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8a

Fig. 8B

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig .13

Fig. 14

Fig. 15

Fig. 16