Abstract

Recent HERA data on the photoproduction of vector mesons are analysed within a "soft", dipole pomeron model. We argued that the data on $\sigma_{el}^{\gamma \rightarrow J/\psi}$ is consistent with a soft pomeron, the apparent rapid increase resulting from the non-asymptotic effects due to the delayed asymptotics of $\sigma_{el}$ with respect to $\sigma_{tot}$. 
Studies of exclusive – diffractive and nondiffractive – photoproduction of vector mesons at HERA have many important new aspects, among which is the applicability of the Regge pole theory for virtual particles, the main subject of the present paper. We construct an explicit Regge-behaved model for virtual particles and discuss its observable consequences in the light of the relevant HERA measurements.

Let us remind that the basic diagram in question is that shown in Fig. 1, where \( s \) and \( t \) are the Mandelstam variables and \( Q^2 = -q^2 \) is the virtuality of the external particle. In most of the cases studied previously, only two variables were present: 1. \( s \) and \( t \) (with \( Q^2 = m^2 \)) for (on-shell) hadronic (exclusive) reactions, and 2. \( s \) and \( Q^2 \) (with \( t = 0 \)) for forward virtual Compton scattering, related by unitarity to deep inelastic (inclusive) scattering. In exclusive virtual photoproduction, on the other hand one has the unique situation when all three variables, \( s, t \) and \( Q^2 \), meet. Moreover, in the photoproduction of heavy mesons, e.g. \( J/\psi \), their masses become another important parameter. In that case, one introduces the sum

\[
q^2 = (Q^2 + M^2)
\]

as a new “scaling” variable, i.e. one assumes that the large mass of the external particle plays the same role as the (photon) virtuality, and consequently \( J/\psi \) production in this sense is “hard”.

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Fig.1. Photoproduction of vector meson.

Fig.2. Quark-gluon picture of vector meson photoproduction. Factorization implies that \( Q^2 \) evolution comes from the upper vertex.
Let us now discuss the "hardness" of the pomeron. According to the HERA data,
\[ \sigma_{el}^{\gamma V} \sim W^n, \]
where \( n = n(\tilde{q}^2) \) tends to increase with increasing "virtuality" \( \tilde{q}^2 \). Typically, \( n \approx 0.22 \div 0.32 \) for elastic photoproduction of light vector mesons and \( n \approx 0.8 \) for deep inelastic photoproduction and/or production of \( J/\psi \). This phenomenon was usually interpreted as the manifestation of two different pomerons – a "soft" \( (n = 4\delta \approx 0.3) \) and a "hard" one \( (n \approx 0.8) \), where \( \delta = \alpha(0) - 1 \) is related to the pomeron intercept.

In this paper we present a different point of view. In our opinion there is only one pomeron in Nature, the variation with \( \tilde{q} \) coming from the relevant vertex as shown in Fig. 2.

In this approach, the pomeron propagator is essentially non-perturbative, while the \( \tilde{q} \)-dependence is given either by the QCD evolution or by the relevant phenomenological vertex function. Factorization is an important property of the theory. It is valid in the case of exchange of a simple pole. In our model factorization holds for the partial amplitude (in the \( (j,t) \)-representation but not in the \( (s,t) \)-one).

Another important aspect of the new HERA data is the possibility to detect a clear pomeron signal in the photoproduction of \( \phi \) and \( J/\psi \), where - by the Okubo-Iizuki-Zweig rule - the contribution from secondary trajectories is suppressed.

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As it is well known, the Regge pole model was formulated within the S-matrix theory, applicable only on the mass shell. Attempts to generalize the Regge pole model for currents were undertaken long ago, with little success, however. A discussion of this problem can be found e.g. in the book [1]. Here we take a pragmatic point attitude in constructing an optimal model combining the known principles of the theory with the observations.

A partial (for \( t = 0 \)) solution to this problem was suggested in the paper [2], in which the inclusive deep inelastic data in a wide range of the variable were fitted by a Regge-type model with a phenomenological expression for the \( Q^2 \)-dependent vertex function. The next step is to extend this model to include \( t \)-dependence as well.

A related approach was pursued in refs. [3, 4], where the \( Q^2 \) dependence was introduced in the parameters of the Regge pole, paticularly in the pomeron intercept \( \alpha_0(Q^2) \). Arguments were presented in that papers on how unitarity constrains this dependence. Notably, \( \alpha_0 \) rises with \( Q^2 \) such as to meet the effect observed at HERA.

Contrary to the above [3] and related papers [5, 6, 7] based on the so-called supercritical pomeron, we use a dipole pomeron pole with unit intercept. Logarithmically rising total cross sections and small-\( x \) structure functions are typical of this class of models. They do not violate the Froissart bound and therefore need not to be unitarized. \( Q^2 \) dependence will be introduced in the parameters of the residue and in the scaling parameter \( s_0 \), but not in pomeron intercept.

Most generally the dipole pomeron model generalized for virtual external particles can be written as follows [2]
\[ A(W, t; \tilde{q}^2) = IP(W, t; \tilde{q}^2) + f(W, t; \tilde{q}^2) + \ldots, \]
where \( IP \) is a Pomeron contribution
\[ IP(W, t; \tilde{q}^2) = ig_0(t; \tilde{q}^2)(\frac{-is}{s_0(\tilde{q}^2)})^{\alpha_0(t)-1} + ig_1(t; \tilde{q}^2)ln(\frac{-is}{s_1(\tilde{q}^2)})^{\alpha_0(t)-1} \]
with \( s = W^2 \) and

\[ g_i(t; \bar{q}^2) = g_i(\bar{q}^2) \exp(b_i(\bar{q}^2)t). \]

A contribution of the \( f \)-reggeons is written similarly:

\[ f(W, t; \bar{q}^2) = ig_f(t; \bar{q}^2) \left( \frac{-is}{s_f(\bar{q}^2)} \right)^{\alpha_f(t)-1}. \]

It is important to note that in this model the intercept of the trajectory equals to 1

\[ \alpha_{IP}(0) = 1. \]

Thus the model does not violate the Froissart-Martin bound.

The parameters of \( \alpha_{IP}(t), \alpha_f(t) \) are universal, independent of the reaction, while \( g_i, b_i, s_i \) are reaction-dependent. In hadronic phenomenology \( g_i \) and \( b_i \) are constants. Here they should be replaced by \( Q^2 \)-dependent functions. The slope \( B(s, t; Q^2) = 2b_i(Q^2) + 2\alpha_f ln(s/s_i(Q^2)) \) contains a universal energy-dependent term, while the parameter \( b_i(Q^2) \) is responsible for the quark content (quark number, masses and flavors).

In this paper we concentrate on the dynamics of the reactions rather than the quark and symmetry relations between them. We just note that the local slope of diffractive \( J/\psi \) production is much smaller than that for other mesons since the heavier \( J/\psi \) is much more compact than the rest of the mesons are.

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For \( \rho, \omega \) and \( \phi \) photoproduction we write the scattering amplitude as a sum of a pomeron and \( f \) contribution. In the case of \( J/\psi \), non-pomeron contributions are suppressed due to the Okubo-Iizuki-Zweig rule. Notice, that although \( \phi \) also consists of strange quarks, it receives - albeit a small - contribution from secondary reggeons due to the \( \omega - \phi \)-mixing. By setting \( A = "IP" + "f" + ... \), we get the integrated elastic cross section \( \sigma_{el} \):

\[
\sigma_{el}^{\gamma^*p\to Vp} = 4\pi \int_{-\infty}^{0} dt |A^{\gamma^*p\to Vp}(W, t; Q^2)|^2
\]

\[
= 4\pi \left\{ \frac{g_0^2}{2B_0} + \frac{g_0 g_1}{B_0 + B_1} \xi + \frac{g_1^2}{2B_1} (\xi^2 + \pi^2/4) + \frac{g_f^2}{2B_f} \left( \frac{s}{s_f} \right)^{2\alpha_f(0)-2} \right. \\
\left. + 2g_f \left( \frac{s}{s_f} \right)^{\alpha_f(0)-1} \left[ \frac{C_f(\xi(B_1 + B_f) + D\pi/2) - S_f(\xi D - (B_1 + B_f)\pi/2)}{(B_1 + B_f)^2 + D^2} \right. \right. \\
\left. \left. + g_0 \frac{C_f(B_0 + B_f) - S_f D}{(B_0 + B_f)^2 + D^2} \right] \right\},
\]

where

\[ C_f = \cos\left( \frac{\pi}{2}(\alpha_f(0) - 1) \right), \quad S_f = \sin\left( \frac{\pi}{2}(\alpha_f(0) - 1) \right) \]

\[ B_i = \alpha'_i ln(s/s_i) + b_i, \quad i = 0, 1, f, \]

\[ D = \frac{\pi}{2}(\alpha'_P - \alpha'_f). \]
\[ \xi = \ln(s/s_1). \]

Generally, \( g_i \) and \( b_i \) may depend on \( q^2 \). However here we consider only the case \( Q^2 = 0 \), therefore we put \( g_i, b_i = \text{const} \) and \( s_i = 1 \text{GeV}^2 \).

Let us first discuss the case of \( J/\psi \). Familiar extrapolations from the old, low-energy data to those from HERA \( \sigma_{el} \sim W^{0.8} \) give a rate of increase much larger than that for total photoproduction, which is \([8, 9] \sigma_{tot} \sim W^{0.2}\). Since the partial cross section for \( J/\psi \) production makes only part of the total cross section the continuation of this trend sooner or later will violate unitarity. Hence one has to assume that the cross sections have not yet reached their asymptotic regimes. This means that either the total cross section will rise faster or that the expected asymptotic rise for \( J/\psi \) is slower than that quoted above.

To illustrate our arguments, we present a fit (without any minimization procedure) to the data on \( \rho, \omega, \phi \) and \( J/\psi \) photoproduction, as well as \( \gamma p \) total cross-section, based on the present model (3). Notice that the sharp rise in the case of \( J/\psi \) at low \( \sqrt{s} \leq 20 \text{GeV} \) is a preasymptotic effect and it is not indicative of the "hardness" of the pomeron. Besides this, the threshold at \( s = (m_p^2 + m_V^2) \) must be taken into account in order to describe the experimental data for \( J/\phi \) and \( J/\phi \) photoproduction. For this case we multiply the amplitude (3) by factor \([1 - (m_p^2 + m_V^2)/s]^{\nu_V}. \) Comparison with the data is illustrated in Fig.3, with the parameters given in the Table.

![Graph](image)

Fig.3. Elastic vector meson production in the model (3).

| Table. Parameters used in Exp.(3) for the description of the experimental data. The values of the slopes \( \alpha_P' = 0.25 \text{GeV}^{-2}, \alpha_f' = 0.85 \text{GeV}^{-2} \) and the intercept \( \alpha_f(0) = 0.8 \) are choosen from hadronic phenomenology. |
Actually, the high-energy part of $\sigma_{el}^{\gamma \rightarrow J/\psi}$ is consistent with a moderate increase with $W$, corresponding to a "soft" pomeron. The apparent rapid increase quoted by different authors is a result of straightforward interpolations from low to high energies without account for the nonasymptotic contribution typical of $\sigma_{el}$. In other words, the onset of the logarithmic asymptotics occurs in $\sigma_{el}$ later than in $\sigma_{tot}$. This is a general feature of the Regge pole or geometrical models and it is shared by the above expression for $\sigma_{el}$. As a consequence, in this type of models the ratio $\sigma_{el}/\sigma_{tot}$ continues rising even after $\sigma_{tot}$ (but not $\sigma_{el}$) has reached its logarithmic asymptotics.

Notice also that the moderate, $\ln(1/x)$ increase of the photoproduction cross-sections is consistent with the recent data on $F_2(x, Q^2)$ from H1 [10], and ZEUS that may be fitted by a $\ln(Q^2)\ln(1/x)$ type expression for not too small and large $Q^2$ [11].

$$\begin{array}{|c|c|c|c|c|c|c|}
\hline
 & g_0, \mu b & g_1, \mu b & g_f, \mu b & b_0, GeV^{-2} & b_1, GeV^{-2} & b_f, GeV^{-2} \\
\hline
\gamma p \rightarrow X & -2.18 & 0.70 & 9.23 & - & - & - \\
\hline
\gamma p \rightarrow pp & -30.10 & 7.75 & 118.4 & 3.89 & 1.83 & 2.32 \\
\hline
\gamma p \rightarrow \omega p & -24.88 & 3.84 & 62.69 & 3.03 & 1.48 & 2.50 \\
\hline
\gamma p \rightarrow \phi p & -5.82 & 1.84 & - & 0.50 & -0.35 & - \\
\hline
\gamma p \rightarrow \psi p & -2.26 & 0.64 & - & 1.06 & 1.10 & - \\
\hline
\end{array}$$

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The presence of the diffractive (dip-bump) structure in the differential cross section is an important indicative of diffraction. This structure is clearly seen in elastic hadronic reactions, namely in $pp$, $\bar{p}p$ and $\pi p$ scattering. The details of this phenomenon, and in particular the evolution with energy as well as the dependence on the masses (radii) of the colliding particles have been studied in details [12, 13]. The dip has been predicted also in other elastic reactions.

Less clear is the dependence of the dip-bump structure on the multiplicities (diffractive dissociation, DD) and virtualities (deep inelastic scattering). Measurements of single DD at high energies extend up to $t \sim -1 GeV^2$. No dip is visible within this kinematical range. Little attention has been paid until now to the appearance of the dip in DD. We are sure that, because of the universal nature of diffraction the dip will show up sooner or later in DD too.

Even less attention has been paid to the possibility of such a structure in deep inelastic scattering. The first evidence of such an event is of great interest.

From most general arguments, the position of the dip depends on two factors: the slope of the first cone (the smaller the slope the further the dip) and the strength of the rescattering (alternatively – the height of the second cone). The slope in diffractive $J/\psi$ production is about $4 GeV^{-2}$ - almost 1/4 of that in $pp$, which has the effect of shifting the dip far away towards
large $|t|$. The possible existence of the dip at values of $|t|$ even smaller than in $pp$ means strong absorption effects (unitarity corrections) at large $q^2$, that may compensate the above trend and shift the dip back to small $|t|$.

In Fig.4 we present the HERA [14] data on the $t-$dependence of the diffractive $J/\psi$ production. The curve is drown to guide the eye. The studies of this interesting phenomenon open a new page in diffractive studies.

Another interesting class of reactions where the dip should also appear is diffractive deep inelastic scattering, where the measurements have recently reached values of about $t = -1 GeV^2$.

![Fig.4. Possible dip-bumb structure in $J/\psi$-production.](image)

The main conclusion of the present paper is that the apparent rapid increase of $\sigma_{\gamma \to J/\psi}^{el}(s)$ above $\sqrt{s} \approx 20 GeV$ is a preasymptotic effect. Asymptotically, this cross-section will level off and will not exceed the rise of $\sigma_{tot}^{\gamma p}$.

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**References**


