Systematic analysis of charmonium photoproduction

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Abstract

The available data on J/Ψ photoproduction are analysed in terms of pomeron exchange, two-gluon exchange and photon–gluon fusion models. Allowing the pomeron–quark interaction to be flavour-dependent and introducing both soft and hard pomerons it is possible to reproduce the data at $\sqrt{s} > 10$ GeV and small $|t|$. The two-gluon exchange calculations indicate strong sensitivity to the gluon distribution function. The results obtained with the most modern MRST2001 and DL PDF reproduce the forward J/Ψ photoproduction cross section at $\sqrt{s} > 10$ GeV. The calculations with the photon–gluon fusion model and with MRST2001 and DL PDF are also in reasonable agreement with the data on the total J/Ψ photoproduction cross section. However none of the models describe the data at $\sqrt{s} < 10$ GeV or $|t| \geq 1$ GeV². We attribute the J/Ψ photoproduction at low energies and large $|t|$ to a mechanism different from pomeron or two-gluon exchange. We consider that this might be the exchange of an axial vector trajectory that couples with the axial form factor of the nucleon.

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1. Introduction

J/Ψ production by real and virtual photons provides an effective way to test QCD dynamics at short distances and to verify QCD inspired models. The pomeron exchange model is one of the nonperturbative QCD approaches traditionally applied [1–6] to vector meson photoproduction at high energies. The crucial point of the model is the flavour independence of the pomeron–quark interaction, which can be studied through systematic analysis of the photoproduction of light, strange, charm and beauty quarks.

Models based on perturbative QCD, such as two-gluon exchange [7–9] and photon–gluon fusion [10–16], provide a direct access to the gluon distribution function. The J/Ψ electro and photoproduction is an excellent tool to test the gluon parton distribution function (PDF).

J/Ψ electroproduction has been studied systematically within these different approaches. Most modern gluon distribution functions, such as MRST2001 [17] and CTEQ6 [18], became available just recently through the analysis of J/Ψ electroproduction at large Q^2 . Very recently the data on J/Ψ electro production were analysed [19] with the photon–gluon fusion model.

Here we present a systematic analysis of J/Ψ production by real photons. We collect old data available at low energies [20–24] as well as data at high energies [25–28] from H1 and ZEUS. We also include very recently published results [29].

Our aim is to investigate whether J/Ψ photoproduction can be understood in terms of a certain model, which is also applicable to the photoproduction of other vector mesons. It is also a crucial line of our study whether the QCD or pQCD models are able to explain the mechanism of J/Ψ photoproduction close to the reaction threshold, i.e. at $\sqrt{s} < 10$ GeV.

2. The difference between ω and J/Ψ photoproduction

The ω , ϕ and J/Ψ vector mesons, which are mixtures of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ and $c\bar{c}$ quark states, have the same quantum numbers. For ideal mixing, θ_V is near 35° , $\phi = s\bar{s}$ and $J/\Psi = c\bar{c}$, while the ω meson is built up with $u\bar{u}$ and $d\bar{d}$. However, the mixing is not ideal and both the ϕ and J/Ψ vector mesons contain a certain fraction of light quarks.

Systematic Regge theory analysis [6] of ω meson photoproduction shows that at large invariant collision energies, $\sqrt{s} \geq 10$ GeV, the reaction is dominated by soft pomeron exchanges, while at $\sqrt{s} \geq 100$ GeV an additional small contribution might come from the hard pomeron. At low energies, $\sqrt{s} < 10$ GeV, ω photoproduction is dominated by meson exchanges. The Regge model with contributions from π and f_2 trajectories reasonably describes the data as well as the standard meson exchange model with π , η and σ contributions. Particularly large contribution from π meson exchange to ω photoproduction at low energies can be understood through the large $\omega \rightarrow \pi + \gamma$ partial decay width, which dominates the ω meson radiative decay mode.

An absolutely different situation holds for the J/Ψ meson. Following Regge theory it is believed that at high energies the J/Ψ meson is produced through soft and hard pomeron exchanges, where the last one dominates at $\sqrt{s} \geq 50$ GeV. It is hard to classify what mechanism is responsible for J/Ψ photoproduction at low energies, below $\sqrt{s} \simeq 10$ GeV. The J/Ψ mass $m_J \simeq 3.097$ GeV is below the $D\bar{D}$ threshold $\simeq 3.739$ GeV and the OZI [30–33] allowed $J/\Psi \rightarrow D + \bar{D}$ decay cannot be realized in vacuum. Instead there are large amounts of OZI suppressed decay channels involving stable hadrons, hadronic resonances and radiative decays [34]. A large fraction of radiative J/Ψ decay proceeds through the production of multi mesonic resonant and non-resonant states. The $J/\Psi \rightarrow \pi + \gamma$ and $J/\Psi \rightarrow \eta + \gamma$ both constitute a negligible part of the total radiative decay modes, thus the single meson exchanges contribution to J/Ψ photoproduction is expected to be very small.

However, it might be that the mesonic or multi-mesonic exchange contribution to $\gamma + N \rightarrow J/\Psi + N$ is negligible and the soft pomeron exchange dominates already starting from the reaction threshold.

The difference between the ω and J/Ψ total photoproduction cross sections is illustrated by figure 1, where the reduced total photoproduction cross section $\sigma_f/\sqrt{s}$ is shown as a function of the photon energy, E_γ . The upper axis of figure 1 indicates the invariant collision energy $\sqrt{s}$, where $s = m_N^2 + 2m_N E_\gamma$ with m_N being the nucleon mass.

The ω photoproduction data are shown by squares and were collected in [6]. The circles show the J/Ψ data taken from [22], where the results available until 1985 were reviewed.

Figure 1. Reduced ω (squares) and J/Ψ (circles and triangles) total photoproduction cross section as a function of photon energy. The ω photoproduction data are collected in [6]. The J/Ψ data available before 1985 are shown by circles and taken from [22]. The J/Ψ photoproduction data at high energies are shown by triangles and are taken from [24–27, 29]. The dashed lines show the calculations with soft pomeron exchange alone, while the solid lines are the sum of soft and hard pomeron contributions. The upper axis indicates the invariant collision energy $\sqrt{s}$.

Part of the J/Ψ photoproduction data [22] was obtained with a nuclear target and therefore should be considered as an average between the proton and neutron. The J/Ψ photoproduction threshold is $E_\gamma \simeq 8.15$ GeV. The Cornell measurement [20] is the only result available now for J/Ψ photoproduction close to the reaction threshold. We note that the J/Ψ photoproduction data measured at $9.0 \leq E_\gamma \leq 11.8$ GeV at Cornell were incorrectly reviewed in [22]. The original experimental numbers for the differential J/Ψ photoproduction cross section were published [20] in the form $d\sigma/dt = (1.01 \pm 0.20) \exp[(1.25 \pm 0.20)t] \text{ nb/GeV}^2$. The total photoproduction cross section is therefore $\sigma = 0.48 \pm 0.12$ nb, taking into account the minimal four momentum transfer squared.

The triangles in figure 1 show the J/Ψ photoproduction data, which appeared after 1985 and are published in [24–29]. It is clear that the energy dependence of $\gamma + p \rightarrow \omega + p$ and $\gamma + N \rightarrow J/\Psi + N$ is different at all photon energies. It is known that this difference at high energies was discovered after the H1 and ZEUS measurements [25–29] at $\sqrt{s} \geq 50$ GeV.

Figure 2 shows the ω and J/Ψ reduced differential photoproduction cross sections, $d\sigma/dt/\sqrt{s}$, extrapolated to zero four momentum transfer squared $t = 0$ as a function of the photon energy E_γ and invariant collision energy $\sqrt{s}$. The energy dependence of the forward photoproduction cross sections again indicates a strong difference between the ω and J/Ψ data. The forward photoproduction cross section is an extrapolation of $d\sigma/dt$ to $t = 0$.

Another value of interest is the exponential slope b of t dependence of the differential photoproduction cross section, which is defined as

$$\left. \frac{d\sigma}{dt} \right|_{t=0} = \left. \frac{d\sigma}{dt} \right|_{t=0} \times \exp(bt), \quad (1)$$

Figure 2. Reduced ω (squares) and J/Ψ (circles and triangles) forward photoproduction cross sections as a function of photon energy. The ω photoproduction data are collected in [6]. The circles show J/Ψ data from [22], while triangles show J/Ψ photoproduction data from [27, 29]. The dashed lines show the calculations with soft pomeron exchange alone, while the solid lines are the sum of soft and hard pomeron contributions.

and is shown in figure 3. Within experimental uncertainties the ω photoproduction data can be well fitted with a constant slope $b = 7.6 \pm 0.1 \text{ GeV}^{-2}$ over a wide range of available photon energies. In contrast, the J/Ψ photoproduction data show a strong energy dependence of the exponential slope. At $E_\gamma < 100 \text{ GeV}$ the data can be reproduced well with a constant slope $b = 2.6 \pm 0.4 \text{ GeV}^{-2}$, while at high energies $b = 5.1 \pm 0.2 \text{ GeV}^{-2}$.

Finally, the available experimental results on ω and J/Ψ meson photoproduction might indicate a rather different mechanism for their production. Although, the quantum numbers of ω and J/Ψ are the same, they have different quark structures. The difference between the ω and J/Ψ photoproduction data can be attributed to the difference between the properties of light and charm quarks, such as their interaction through the gluon exchange, confinement and fusion into real hadrons and photon quark–antiquark fluctuation. Therefore, currently available theoretical models for ω and J/Ψ meson photoproduction are inspired by QCD.

In the next section we review the models that recently were successfully applied to the J/Ψ electroproduction off the nucleon. We will compare these models with data on J/Ψ photoproduction by real photons. Furthermore, we consider all available data on J/Ψ photoproduction in order to do our study in a more systematic way.

3. Pomeron exchange model

The basis of the model is the factorization of the exclusive vector meson photoproduction amplitude in terms of the product of $\gamma \rightarrow q + \bar{q}$ fluctuation, the scattering of the $q\bar{q}$ system by the proton and finally the $q\bar{q}$ hadronization into a vector meson. The interaction between

Figure 3. The slope, b , of the t dependence of the differential ω (squares) and J/Ψ (circles) photoproduction cross sections as a function of photon energy, E_γ , and invariant collision energy, $\sqrt{s}$. The data are from [6, 22, 27, 29]. The solid lines show the calculations with soft pomeron exchange alone for ω photoproduction and with the sum of soft and hard pomeron contributions for J/Ψ photoproduction. The calculations show the energy dependence of the local slope at the indicated four momentum transfer squared, t . The dashed lines show the fits using a constant value. The J/Ψ photoproduction data were fitted separately at photon energies below and above 100 GeV.

the $q\bar{q}$ state confined in the vector meson and the nucleon is taken to be given by pomeron exchange. The pomeron propagator $G(s, t)$ is parametrized as

$$G(s, t) = i \left(\frac{s}{s_0} \right)^{\alpha(t)-1} \exp \left(-\frac{i\pi}{2} [\alpha(t) - 1] \right), \quad (2)$$

and therefore the pomeron trajectory $\alpha(t)$ drives the $\sqrt{s}$ energy dependence of the reaction amplitude. The evolution of the t dependence with energy is controlled by the pomeron exchange trajectory as well.

The interaction between the pomeron and quark is considered to be flavour independent. The flavour independence of the quark–pomeron interaction might provide a unique way to construct a unified model for vector meson photoproduction.

3.1. Soft pomeron

The pomeron exchange amplitude $\mathcal{T}$ for vector meson photoproduction is depicted in figure 4(a) and is explicitly given [1–5] in the form

$$\mathcal{T} = 3iF_1(t) \frac{8\sqrt{6}m_q e_q f_V \beta_q^2}{4m_q^2 - t} (\varepsilon \cdot \varepsilon_V) \left(\frac{s}{s_0} \right)^{\alpha(t)-1} \exp \left[-\frac{i\pi}{2} (\alpha(t) - 1) \right] \frac{\mu_q^2}{2\mu_q^2 + 4m_q^2 - t}, \quad (3)$$

Figure 4. The diagrams for pomeron exchange (a), two-gluon exchange (c, d) and photon–gluon fusion model (b).

where e_q and m_q are the charge and mass of the quark, ε and ε_V are the polarization vectors of the photon and vector meson, respectively and f_V is the meson decay constant given by $V \rightarrow e^+e^-$ radiative decay width $\Gamma_{e^+e^-}$ as

$$\Gamma_{e^+e^-} = \frac{8\pi\alpha^2 e_q^2}{3m_V} f_V^2, \quad (4)$$

where α is the electromagnetic coupling constant and m_V is the vector meson mass.

Furthermore, t is the squared four momentum transfer and $F_1(t)$ is the proton isoscalar EM form factor given as

$$F_1(t) = \frac{4m_p^2 - 2.8t}{4m_p^2 - t} \frac{1}{(1 - t/t_0)^2}, \quad (5)$$

with m_p being the proton mass and $t_0 = 0.71 \text{ GeV}^2$. The $F_1(t)$ was introduced assuming the pomeron resembles an isoscalar photon.

The pomeron trajectory $\alpha(t)$ for soft pomeron exchange is given as

$$\alpha(t) = 1.08 + \alpha' t, \quad (6)$$

with $\alpha' = 0.25 \text{ GeV}^{-2}$. The constant s_0 is not well-defined theoretically and can be taken as $s_0 = 1/\alpha'$ following the dual model prescription [35].

The free model parameter, β_q , determines the strength of the effective pomeron coupling with the quark, while μ_q accounts for the possibility that the coupling with an off-shell quark is not pointlike but dressed with the form factor given by the last term of equation (3). Both β_q and, in principle, μ_q might depend on the flavour of the quark and can be fixed by experimental data.

The phase of the soft pomeron exchange amplitude was not written explicitly in [1–5] since no interference with other exchanges was considered.

The amplitude is normalized so that $d\sigma/dt = \alpha|T|^2$. Finally, the differential $\gamma + p \rightarrow V + p$ cross section due to soft pomeron exchange is given for a real photon as,

$$\frac{d\sigma}{dt} = \frac{81m_V^3 \beta_q^4 \mu_q^4 \Gamma_{e^+e^-}}{\pi\alpha} \left(\frac{s}{s_0}\right)^{2\alpha_{P_1}(t)-2} \frac{F_1^2(t)}{(m_V^2 - t)^2 (2\mu_q^2 + m_V^2 - t)^2}, \quad (7)$$

where it was assumed that $m_V = 2m_q$.

Figure 5. The ratio of $\gamma + p \rightarrow \omega + p$ to $\gamma + p \rightarrow \rho + p$ cross sections as a function of photon energy, E_γ , and invariant collision energy, $\sqrt{s}$. The solid line shows the ratio of the $\omega \rightarrow e^+e^-$ and $\rho \rightarrow e^+e^-$ decay widths. The dashed line shows the fit to data with a constant value of $R = 0.115 \pm 0.003$.

The coupling constant β_q and the form factor μ_q were fitted [6] through a systematic analysis of ω meson photoproduction as

$$\beta_q = 2.35 \text{ GeV}^{-1}, \quad \mu_q^2 = 1.1 \text{ GeV}^2. \quad (8)$$

It was found [6] that the parameter β_q evaluated from ω photoproduction was different from $\beta_q = 2.0 \text{ GeV}^{-1}$ needed in the description [36, 37] of ρ photoproduction data. This discrepancy could not be explained in a satisfactory way, since once the parameters of the pomeron exchange are fixed by ρ meson photoproduction, they should be applicable to the other vector mesons as well. Moreover, at this stage we still do not discuss the flavour dependence of the quark–pomeron interaction, because we are dealing with ρ and ω photoproduction, i.e. light $q\bar{q}$ states.

An ideal illustration of this finding is given by the ratio of the $\gamma + p \rightarrow \omega + p$ and $\gamma + p \rightarrow \rho + p$ cross sections, shown in figure 5 as a function of photon energy E_γ and invariant collision energy $\sqrt{s}$. Following equation (7) the ratio of ω and ρ meson photoproduction is given by the ratio of $\omega \rightarrow e^+e^-$ and $\rho \rightarrow e^+e^-$ decay widths

$$\frac{\Gamma_{\omega \rightarrow e^+e^-}}{\Gamma_{\rho \rightarrow e^+e^-}} = \frac{0.60 \pm 0.02 \text{ keV}}{6.77 \pm 0.32 \text{ keV}} = 0.088 \pm 0.005, \quad (9)$$

which is shown by the solid line in figure 5 and considerably underestimates the experimental results.

The dashed line in figure 5 shows the fit to the data by a constant value $R = 0.115 \pm 0.003$, which is close to the $SU(3)$ estimates for the ω and ρ coupling with the photon. Finally the difference between the Regge model and the data accounts for a factor of $\simeq 1.3$. It is already clear that both ρ and ω photoproduction data could not be reproduced by the soft pomeron exchange simultaneously with the same set of parameters β_q and μ_q .

Now, the dashed line in figure 1 shows the contribution from soft pomeron exchange to the total reduced ω meson photoproduction cross section. The calculations were done with the parameters given by equation (8). The comparison with differential $\gamma + p \rightarrow \omega + p$ cross sections at different photon energies is given in [6]. The contribution from soft pomeron exchange to forward ω meson photoproduction is shown in figure 2 by the dashed line.

Obviously, the soft pomeron exchange alone will reproduce the ω photoproduction data at $\sqrt{s} \geq 6$ GeV. At lower energies the dominant contribution to the $\gamma + p \rightarrow \omega + p$ reaction comes from meson exchanges.

The t dependence of the photoproduction cross section arising from the soft pomeron exchange is given by the proton EM form factor squared $F_1^2(t)$, the quark–pomeron form factor squared and by the pomeron exchange trajectory $(s/s_0)^{2\alpha(t)-2}$. The exponential slope, b , of the t dependence can be evaluated as

$$b = \frac{d}{dt} \ln \left[\frac{d\sigma}{dt} \right], \quad (10)$$

from the differential photoproduction cross section given by equation (7).

The slope due to the proton isoscalar EM form factor is

$$b_1 = -\frac{5.6}{4m_p^2 - 2.8t} + \frac{2}{4m_p^2 - t} + \frac{4}{t_0 - t}, \quad (11)$$

and since it depends on t it can be considered as a local slope. At $t = 0$ the slope from proton EM form factor is $\simeq 4.6$. The slope due to the quark–pomeron form factor squared is given as

$$b_2 = \frac{2}{m_V^2 - t} + \frac{2}{2\mu_q^2 + m_V^2 - t}, \quad (12)$$

and depends on the cutoff parameter μ_q and mass of the produced vector meson m_V . For ω meson photoproduction at $t = 0$ the slope associated with the quark–pomeron form factor is $\simeq 4.0$. The energy dependence of the slope comes from the pomeron trajectory and is given for soft pomeron exchange as

$$b_3 = 0.5 \ln(0.25s). \quad (13)$$

Finally, the total exponential slope, b , of the t dependence for ω meson photoproduction at $t = 0$ has a minimum value of $b = 8.6 \text{ GeV}^{-2}$ and increases logarithmically with energy. This result is in excellent agreement with the data shown in figure 3. Here we also show the local slope b at different squared four momentum transfers t . It is also clear that the appearance of the proton EM form factor in the reaction amplitude dictates quite a large value of the minimal available b at $t = 0$.

The total exponential slope of the t dependence for J/Ψ meson photoproduction at $t = 0$ has a minimum value of $b = 4.97 \text{ GeV}^{-2}$ since $b_2 = 0.37 \text{ GeV}^{-2}$. This result is in reasonable agreement with the data at $\sqrt{s} > 10$ GeV shown in figure 3.

The contribution from the soft pomeron exchange to J/Ψ photoproduction is given by equation (7). Taking the parameters β_q and μ_q as determined from the data on ω meson photoproduction, one can easily estimate the ratio of forward J/Ψ and ω photoproduction cross sections as

$$R \left(\frac{J/\Psi}{\omega} \right) = \frac{\Gamma_{J \rightarrow e^+e^-}}{\Gamma_{\omega \rightarrow e^+e^-}} \frac{m_\omega(m_\omega^2 + 2\mu_q^2)}{m_J(m_J^2 + 2\mu_q^2)} = 0.13, \quad (14)$$

with $\Gamma_{J \rightarrow e^+e^-} = 5.26 \text{ keV}$. The experimental results shown in figure 2 indicate that this ratio is of the order 0.005 at $\sqrt{s} \simeq 10$ GeV. Therefore the soft pomeron exchange with fixed parameters for the quark–pomeron interaction substantially overestimates the data on

J/Ψ photoproduction. However, since it was already realized that a simultaneous description of both ρ and ω photoproduction data requires a different coupling constant β_q , one might proceed in a similar way and readjust β_q to the J/Ψ photoproduction data.

Considering the flavour dependence of the interaction between the pomeron and quark one might distinguish the light quark coupling $\beta_u = \beta_d = 2.35 \text{ GeV}^{-1}$, which is taken to be the same as evaluated from ω meson photoproduction and the pomeron coupling with charm quark β_c . In that case the β_q^2 term in the amplitude given by equation (3) should be replaced by the product $\beta_u \beta_c$. In addition the differential cross section of equation (7) must also be corrected.

We found that the choice of $\beta_c = 0.45 \text{ GeV}^{-1}$ provides a reasonable description of the data around $\sqrt{s} \simeq 10 \text{ GeV}$. The dashed lines in figures 1 and 2 show our calculation of the soft pomeron contribution to the reduced total and forward J/Ψ photoproduction cross section.

However, resolving the problem with the reduction of the soft pomeron contribution to J/Ψ photoproduction leaves one far short of a description of the J/Ψ meson data collected in figures 1, 2 and 3.

First, although the soft pomeron seems to reproduce the total J/Ψ photoproduction cross section starting just from the reaction threshold, the model absolutely fails to describe the forward cross section and slope b of the t dependence at $\sqrt{s} < 10 \text{ GeV}$. The minimal value of the slope is given by the proton scalar EM form factor and the total exponential slope of the t dependence for J/Ψ photoproduction has a minimal value of $b \simeq 5 \text{ GeV}^{-2}$ at $t = 0$. This is already larger than the experimental results at low energies where $b < 3 \text{ GeV}^{-2}$.

Second, the energy dependence of the total and forward J/Ψ photoproduction cross section and the slope b at high energies cannot be reproduced by soft pomeron exchange.

3.2. Hard pomeron

There are different attempts to reproduce the energy dependence of the total J/Ψ photoproduction cross section without introducing a new pomeron trajectory. The strategy is to readjust the t dependence in such a way that it becomes flatter, providing the correct total cross section after integration over the large t region accessible at high energies. One of the more natural ways is to introduce a trajectory that is nonlinear in t , instead of that given by equation (6). Obviously the J/Ψ photoproduction data at $t = 0$, shown in figure 2, do not support such solution.

Instead, the forward J/Ψ photoproduction cross section requires that at $t = 0$ the cross section is proportional to $\sqrt{s}$, because the reduced cross section in figure 2 is almost independent of energy for $\sqrt{s} > 10 \text{ GeV}$. From equation (2) one can show that the trajectory necessary to reproduce the data has an intercept $\alpha(t = 0) \simeq 1.25$. Moreover, since the energy dependence of the slope, b , is proportional to $\alpha' \ln(s)$, the data shown in figure 3 support the value of $\alpha' \simeq 0 \text{ GeV}^{-2}$.

The hard pomeron trajectory was introduced in [4] as

$$\alpha(t) = 1.44 + 0.1t. \quad (15)$$

The calculations with both hard and soft pomeron exchanges, including their interference, are shown by the solid lines in figures 1, 2 and 3. The coupling constant between the hard pomeron and the charm quark was fitted as $\beta_c = 0.05 \text{ GeV}^{-1}$. The calculations reproduce quite well the data on total and forward J/Ψ photoproduction cross section and slope b of the t dependence at $\sqrt{s} \geq 10 \text{ GeV}$. Note that for both soft and hard pomeron exchanges the partial slope b_2 , coming from the form factor in the upper pomeron–quark vertices, is $b_2 \simeq 0.37$, because of the large J/Ψ mass appearing in equation (11). It is clear that the hard pomeron dominates at high energies.

Figure 6. The $\gamma + p \rightarrow J/\psi + p$ differential cross section as a function of four momentum transfer squared, t , measured at different invariant collision energies $\sqrt{s}$ by H1 Collaboration [27]. The solid lines show the calculations including both soft and hard pomeron exchanges.

Figure 6 shows the differential cross section for J/ψ photoproduction at high energies. The data available at small t can be described well by the model.

While the introduction of a hard pomeron exchange allows one to resolve inconsistencies at high energies, the discrepancies between the model and the data at $\sqrt{s} < 10$ GeV still remain.

The most crucial data are shown in figure 7, where we collect available data on differential $\gamma + N \rightarrow J/\psi + N$ cross section at relatively small energies, $\sqrt{s} < 23$ GeV. The solid lines show the calculations with soft and hard pomeron contributions. The dashed lines show the fit to the soft part of the differential spectra.

The comparison between the differential spectra and calculations at $\sqrt{s} < 10$ GeV illustrates that both slope and extrapolated cross section at $t = 0$ could not be reproduced by the model. The rough agreement between the integrated theoretical and experimental cross sections shown in figure 1 should be considered as an accident. The pomeron exchange model is far from describing the data at $\sqrt{s} < 10$ GeV.

Figure 7 shows that at $\sqrt{s} \simeq 20$ GeV the pomeron exchange allows one to describe the steep dependence of the differential $\gamma + N \rightarrow J/\psi + N$ cross section at small t . At large four momentum transfer squared there are additional contributions resulting in a soft component of the spectrum. It is worthwhile to note that the slope of the soft component observed at $\sqrt{s} \simeq 20$ GeV is close to that measured at lower energies and is around $0.7 \div 2.8 \text{ GeV}^{-2}$.

Figure 8 shows recent data on differential $\gamma + N \rightarrow J/\psi + N$ cross sections collected by the ZEUS Collaboration [29] at $30 \leq \sqrt{s} \leq 170$ GeV. The solid lines show the calculations with soft and hard pomeron contributions, which well describe the data at low $|t|$. At large four momentum transfer squared we detect a soft component of the spectrum [38–40].

Figure 7. The $\gamma + p \rightarrow J/\psi + p$ differential cross section as a function of four momentum transfer squared t measured at different invariant collision energies $\sqrt{s}$. The data are from Cornell [20], E687 [24], EMC [23] and SLAC Collaboration [21]. The solid lines show the calculations including both soft and hard pomeron exchanges. The dashed lines indicate the fit to the soft part of the spectra.

3.3. Short comment

It is clear that assuming the appropriate flavour dependence of the interaction between pomerons and quarks, the Regge model allows an excellent description of the high energy and low t data on vector meson photoproduction.

There are attempts to recover flavour independence by accounting for mass-dependent corrections, such as Fermi motion and quark off-shellness in the $q\bar{q}$ loop. Indeed the vector meson coupling with $q\bar{q}$ introduced through equation (4) was obtained within an on-shell approximation, which is not correct in the case of diffractive photoproduction. However, it was found that calculations [41–43] with realistic vector meson wavefunctions do not allow one to describe simultaneously the ρ and J/ψ meson electroproduction, similar to what we have found in the present study of ω and J/ψ photoproduction by real photons. It was proposed to use a Gaussian wavefunction instead and to regulate its mean value individually for each vector meson. It is not clear whether such degree of freedom is better than the individual choice of coupling constant β_q .

4. Two-gluon exchange model

The exclusive vector meson photoproduction amplitude is again factorized in terms of the $\gamma \rightarrow q + \bar{q}$ fluctuation, the scattering of the $q\bar{q}$ system by the proton and finally the $q\bar{q}$ hadronization into the vector meson. The $q\bar{q}$ system interacts with a nucleon through two-gluon exchange.

Figure 8. The $\gamma + p \rightarrow J/\psi + p$ differential cross section as a function of four momentum transfer squared t measured at different invariant collision energies $\sqrt{s}$ by the ZEUS Collaboration [29]. The solid lines show the calculations including both soft and hard pomeron exchanges.

In lowest order perturbative QCD the photoproduction amplitude is given by the sum of two diagrams depicted in figures 4(b) and (c) and can be written as [7–9]

$$\mathcal{T} = \frac{i2\sqrt{2}\pi^2}{3} m_q \alpha_s e_q f_V F_{2g}(t) \int dl^2 D_g^2(l) [D_+(l) - D_-(l)] G(l), \quad (16)$$

where the integration is performed over the gluon transverse momentum, e_q and m_q are the charge and mass of the quark, respectively, while α_s is the QCD coupling constant [34]. The meson decay constant is given by equation (4). The gluon propagator $D_g(l)$ is taken as $1/l^2$, the $D_-(l)$ is the propagator of the off-shell quark in the diagram where each gluon couples with a different quark of the vector meson and is given as

$$D_-(l) = (-2m_q^2 - 2l^2)^{-1}. \quad (17)$$

When the two gluons couple with the same quark the off-shell quark propagator is

$$D_+(l) = (-2m_q^2)^{-1}. \quad (18)$$

Furthermore, $F_{2g}(t)$ accounts for the t dependence of the amplitude given by a two gluon correlation in the proton. The form factor $F_{2g}(t)$ is not defined by the model and, as proposed in [7], can be taken to be the proton isoscalar EM form factor, $F_1(t)$, given by equation (5).

Figure 9. The gluon distribution functions as a function of x at $Q^2 = m_J^2$. Upper axis shows the relevant invariant collision energy given as $\sqrt{s} = m_J/\sqrt{x}$. The functions are taken from [44, 45, 17–19].

Function $G(l)$ defines the probability of catching the two gluons with momenta l from the proton and it is related to the conventional gluon distribution function $g(x)$ as [7, 8]

$$xg(x, Q^2) = \int^{Q^2} dl^2 \frac{G(l)}{l^2}. \quad (19)$$

Finally the two-gluon exchange amplitude becomes

$$\mathcal{T} = \frac{i\sqrt{2}\pi^2}{3} m_q \alpha_s e_q f_V F_{2g}(t) \left[\frac{xg(x, Q_0^2)}{m_q^4} + \int_{Q_0^2}^{+\infty} \frac{dl^2}{m_q^2(m_q^2 + l^2)} \frac{\partial xg(x, l^2)}{\partial l^2} \right]. \quad (20)$$

The amplitude is normalized so that $d\sigma/dt = \alpha |\mathcal{T}|^2$ and in lowest order the J/Ψ photoproduction cross section is given as

$$\frac{d\sigma}{dt} = \frac{\pi^3 \Gamma_{e^+e^-} \alpha_s}{6\alpha m_q^5} [xg(x, m_J^2)]^2, \quad (21)$$

where $x = m_J^2/s$. The cross section depends on the gluon distribution function squared and the energy dependence of $d\sigma/dt$ is directly given by the x dependence of $xg(x)$.

To compare the two-gluon exchange model with data on J/Ψ photoproduction, we need to specify the gluon parton distribution function. The PDF used in the following calculations are shown in figure 9 as a function of x and for $Q^2 = m_J^2$. The upper axis of figure 9 indicates the relevant invariant collision energy, $\sqrt{s} = m_J/\sqrt{x}$. The old GRV98 [44] and MRSG [45] functions show a very steep dependence at small x , while the most modern MRST2001 [17] and CTEQ6 [18] functions are almost flat in x . The DL [19] structure function shows some average dependence between the two extreme GRV98 and MRST2001 cases.

The PDF shown in figure 9 are very similar for $x \geq 0.01$, which corresponds to the invariant collision energy of $\sqrt{s} < 30$ GeV. That means that the data available before H1

Figure 10. The forward J/ψ photoproduction cross section [22, 27, 29] as a function of photon energy, E_γ . The lines show the pQCD calculations by the two-gluon exchange model with the gluon distribution functions GRV98 [44], MRST2001 [17] and DL [19]. The upper axis indicates the invariant collision energy.

and ZEUS measurement are not sensitive to the choice of PDF. One might expect that the differences between the different gluon functions in reproducing the $\gamma + p \rightarrow J/\psi + p$ reaction should appear only at high energies. Since $xg(x)$ enters the photoproduction cross section as an unintegrated function squared, the sensitivity of the energy dependence of J/ψ photoproduction to the type of PDF should be extremely high.

The calculations were done for two extreme cases given by GRV98 and MRS2001 and for the DL function. The energy dependence of the QCD coupling constant α_s was taken from [34]. The mass of the charm quark allows for additional freedom in the absolute normalization of the calculations and we used $m_q = 1.3$ GeV. Figure 10 shows the forward $\gamma + p \rightarrow J/\psi + p$ cross section as a function of the photon energy in comparison to the two-gluon exchange model calculations by equation (21) with different gluon distribution functions.

As expected, the different PDF equally well reproduce the data around $\sqrt{s} \simeq 10$ GeV. The GRV98 function is too steep at small x to describe the J/ψ photoproduction at high energies. The DL function reasonably well reproduces the data over a wide range of photon energies, but has an incorrect threshold dependence, because of its asymptotic behaviour at large $x \simeq 1$, as can be seen from figure 9.

The modern MRST2001 gluon distribution function describes the energy dependence of the forward J/ψ photoproduction cross section very well, providing as well the correct threshold behaviour. It is also important to note that the two-gluon model calculations with MRST2001 leave some room for contribution from other processes at $\sqrt{s} < 8$ GeV. As is illustrated by figures 1, 2 and 3 the data actually require a different photoproduction mechanism close to the threshold, which certainly can be added to the two-gluon exchange contribution.

The t dependence of the two-gluon exchange is introduced artificially through the proton EM form factor F_1 providing the slope $b = 4.6$ GeV $^{-2}$ at $t = 0$. Although this result is in

agreement with the data shown in figure 3 one may consider this agreement as a reasonable guess. Obviously the two-gluon exchange cannot describe the slope at $\sqrt{s} < 10$ GeV.

5. Photon–gluon fusion model

In the photon–gluon fusion model [10–16] (PGF) the photon fuses with a gluon from the nucleon and forms a $c\bar{c}$ pair, as is shown in diagram in figure 4(b). Since a gluon transforms as a colour octet, the produced $c\bar{c}$ pair must radiate a soft gluon before the hadronization into the colour singlet final state. Therefore the PGF presumably consider an inclusive charmonium or open charm photoproduction associated with excitation of the final nucleon.

The model convoluted the gluon momentum distribution and the photon–gluon cross section $\sigma_{\gamma g \rightarrow c\bar{c}}$, which is given as

$$\sigma_{\gamma g \rightarrow c\bar{c}} = \frac{2\pi\alpha e_c^2\alpha_s}{\tilde{s}^3} \left([\tilde{s}^2 + 4m_c^2(\tilde{s}^2 - 2m_c^2)] \ln \left[\frac{1+\beta}{1-\beta} \right] - \beta[\tilde{s}^2 + 4\tilde{s}m_c^2] \right), \quad (22)$$

where e_c and m_c are the charge and mass of the charm quark, respectively, α_s is the QCD coupling constant, α is the electromagnetic coupling constant, $\tilde{s}$ is the squared invariant mass of the photon–gluon system and

$$\beta^2 = 1 - \frac{4m_c^2}{\tilde{s}}. \quad (23)$$

The PGF does not consider explicitly the formation of the final state which should enter through the J/Ψ wavefunction as in the case of the two-gluon exchange model. Instead the convolution of the photon–gluon cross section with the gluon momentum distribution is performed over the range from the charmonium production threshold, $2m_c$, up to the open charm production threshold $2m_D$, given by the mass of the D meson. Finally the charmonium photoproduction cross section is

$$\sigma = f \int_{4m_c^2}^{4m_D^2} \frac{d\tilde{s}}{\tilde{s}} \sigma_{\gamma g \rightarrow c\bar{c}} g \left(x = \frac{\tilde{s}}{s}, m_J^2 \right), \quad (24)$$

where the factor, f , is an adjustable parameter that accounts for the fraction of the specific charmonium bound states available in the mass region between $2m_c$ and $2m_D$. For the J/Ψ meson we fit it as $f = 0.062$ with $m_c = 1.3$ GeV. However, it was not justified in the PGF model that the factor f is energy independent for the diffractive photoproduction.

The PGF calculations with different gluon distribution functions are shown in figure 11, together with data on the total $\gamma + p \rightarrow J/\Psi + p$ reaction cross section. Obviously, the PGF is less sensitive to the type of gluon distribution functions in comparison to the two-gluon exchange model. The calculations with MRST2001 [17] and DL [19] reproduce the data better than the results obtained with GRV98 [44], which indicates a much steeper energy dependence. However the MRST2001 and GRV98 distributions both have the correct threshold behaviour, while DL—has not. In principle, the DL gluon distribution function can be corrected in order to get the correct asymptotic behaviour as $x \rightarrow 1$, by multiplying it with $(1-x)^5$. However, then the agreement with the data disappears.

The PGF model does not contain a t dependence and in the best case it can be artificially introduced through the proton EM form factor. Although the PDF calculations are able to reproduce the cross section for J/Ψ photoproduction starting from the threshold, we would not claim that pQCD is able to describe the data at $\sqrt{s} \leq 10$ GeV. We consider this good agreement between the data and PGF calculations due to the correct asymptotic behaviour of the gluon distribution function as $x \rightarrow 1$, given by $\simeq(1-x)^5$ dependence. Figure 11

Figure 11. The total J/Ψ photoproduction cross section [22, 24–27, 29] as a function of photon energy, E_γ . The lines show the pQCD calculations by photon–gluon fusion model with the gluon distribution functions GRV98 [44], MRST2001 [17] and DL [19]. The upper axis indicates the invariant collision energy.

shows this function alone in order to illustrate its threshold dependence. Furthermore, in the two-gluon exchange model the PDF enters squared and the near threshold behaviour of the J/Ψ photoproduction cross section is then given by the function $\simeq (1-x)^{10}$, which is shown in figure 10. However, now the dependence is too steep to reproduce the data near the threshold.

6. Conclusion

We have analysed the available data on J/Ψ photoproduction in terms of pomeron exchange, two-gluon exchange and photon–gluon fusion models.

Allowing the pomeron–quark interaction to be flavour-dependent and introducing both soft and hard pomerons it is possible to reproduce almost all of the available data on J/Ψ photoproduction at $\sqrt{s} > 10$ GeV and small $|t|$. At the same time, the model reproduces the data on ω meson photoproduction quite well, again taking into account that the interaction of the pomeron with light and charm quarks is very different. However the pomeron exchange model cannot reproduce the data at $\sqrt{s} < 10$ GeV or the differential spectra at large $|t|$. The agreement between the calculations and total J/Ψ photoproduction cross section near the threshold should be considered as accidental, because both the slope b of the t dependence and the forward extrapolated cross section are in strong systematic disagreement with the pomeron exchange model at $\sqrt{s} < 10$ GeV.

The two-gluon exchange pQCD calculations indicate strong sensitivity to the gluon distribution function. The results obtained with the most modern MRST2001 [17] and DL [19] PDF reproduce the forward J/Ψ photoproduction cross section at $\sqrt{s} > 10$ GeV quite well. The calculations with MRST2001 show the correct threshold dependence of the cross section and leave room for a contribution from other mechanisms at low energies. The

two-gluon exchange model does not contain any t dependence. Its artificial introduction through the isoscalar EM proton form factor allows one to reproduce the slope of the t dependence at high energies, but fails at $\sqrt{s} < 10$ GeV.

The calculations with the photon–gluon fusion model again show sensitivity to the gluon distribution function. The PGF results calculated with MRST2001 [17] and DL [19] PDF are in reasonable agreement with the data on the total J/Ψ photoproduction cross section. The PGF does not constrain the t dependence.

Although the PGF calculations with MRST2001 reproduce the threshold behaviour of the total $\gamma + p \rightarrow J/\Psi + p$ cross section it does not prove that pQCD is able to describe the reaction at $\sqrt{s} < 10$ GeV. It is just an artefact of the correct PDF asymptotic behaviour at $x \rightarrow 1$, given by $\simeq(1-x)^5$ dependence. For instance, this is not the case for the two-gluon exchange model, where the PDF enters squared and finally the $\simeq(1-x)^{10}$ dependence is too steep to reproduce the J/Ψ photoproduction data near the threshold.

We suggest that the J/Ψ photoproduction at low energies and large $|t|$ can be explained by a mechanism different from either the pomeron or two-gluon exchange model. The energy dependence of the differential cross section, $d\sigma/dt$, indicates that this mechanism does not depend on s . Furthermore, the small slope, b , of the t dependence indicates that the exchange does not couple with the isoscalar EM proton form factor. We consider that this might be an axial vector trajectory exchange that couples with the axial form factor of the nucleon. However, a definite conclusion requires a more detailed study.

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