Is there window for “supersoft” Pomeron in $J/\psi$ photoproduction at low energy?

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Abstract

The low energy $J/\psi$ photoproduction cross-section has been studied upon the basis of the Pomeron model. To incorporate the discrepancy between experimental data and predictions by conventional models, i.e. the sum of the soft Pomeron with intercept 1.08 and the hard Pomeron with intercept 1.418, a Regge trajectory associated with a scalar meson ($f$, $a$) exchange which we call “supersoft” Pomeron, is introduced additionally. To distinguish between the conventional model and this new additional Pomeron, observations related to other polarization observables in upcoming polarized experiments are discussed.

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1. It is well-known that exclusive photoproductions of light vector mesons $\rho$, $\omega$, and $\phi$ have been characterized by a weak dependence of the cross-section on the photon-proton center of mass energy $W$ and by a diffractive peak, i.e. small scattering angle of the vector meson with respect to the incident photon direction. This behavior has been explained by the Vector Dominance Model (VDM) and Regge theory [1]. Regge theory has dominated various aspects of high energy particle physics [2]. It is considered to be applicable in the region where $W^2$ is much greater than other variables. But surprising thing is that it works sometimes very well even at considerably smaller energy, close to the threshold [3]. As stated above, the data on production of the light vector mesons at high energies have been well explained in this theory by the exchange of a single nonperturbative Pomeron [4, 5, 6, 7, 8, 10], which is known as the “soft-Pomeron” [11] with trajectory

$$\alpha_s(t) = \alpha(0) + \alpha' t = 1.0808 + 0.25t.$$  

When the energy dependence of the vector-meson production cross-section is parameterized as $W^\delta$ (in the Regge theory approach, $\delta = 4(\alpha_s(0) - 1 - \alpha'/b)$, where $b$ is the slope of the $t$-distribution with typical value $b = 10$ GeV$^{-2}$), then for light vector mesons, $\delta \simeq 0.22$ is found to be a good value for reproducing the data.

One widely discussed problem arises when this model is applied to $J/\psi$ productions at large energy for $W > 10$ GeV [1]. The cross-section for exclusive $J/\psi$ productions by quasi-real photons ($Q^2 = 0$) at HERA is observed to rise more steeply with $W$. Parameterization shows that in this case $\delta \simeq 0.8$, contrary to the theoretical expectation with $\delta \simeq 0.2$. This steep energy dependence is different from the “soft” behavior of light vector mesons, and is known as the “hard” behavior of $J/\psi$ meson. There are two basic approaches for explaining this discrepancy: perturbative two-gluon contribution [12, 13, 14] and the contribution of the hard Pomeron by Donnachie and Landshoff [11].

Another problem is related to the low energy region. Previous analysis by Donnachie and Landshoff (DL) for description of various hadronic reactions with hadrons consisting of light $u, d, s$ quarks shows that the low energy behavior may be successfully parameterized by a single effective Regge pole whose trajectory has intercept $\alpha = 0.5475$ [15]. For simplicity, in this paper we call this contribution as a “supersoft” trajectory or ”supersoft” Pomeron. Note that the physical background for introducing this trajectory is not obvious in the case of light quarks/hadrons because the conventional low-order meson-exchange may contribute just at low energy. However,
the situation is different in photoproduction of $J/\psi$-meson which consists of $c, \bar{c}$ quark and thus, conventional meson exchange dynamics is forbidden. In this case the idea of contribution of the additional "supersoft" Pomeron seems to be more natural. Besides the above mentioned DL-supersoft Pomeron, another possible contribution of the trajectory inspired by $(J^\pi = 0^+, M^2 \sim 3 \text{ GeV}^2)$ glueball predicted by Lattice QCD and QCD motivated models, has been also discussed in literature [16, 17]. In this paper, we concentrate mainly on this subject of $J/\psi$ photoproduction and analyze the possible manifestation of the supersoft Pomeron at low energy.

2. The Pomeron being a gluonic assembly has long been established both theoretically and experimentally [18]. Based on the Pomeron model, to explain the "hard" or steep $W^2$ behavior of $J/\psi$ photoproductions, many models have been proposed so far, among which two typical models are remarkable: (a) the two-gluon models motivated by perturbative QCD widely discussed in literature [12, 13, 14] and (b) the phenomenological model motivated by the non-perturbative QCD and Regge theory [11], i.e. hard Pomeron exchange with intercept 1.418. Our main interest here is the low energy region where the model (a) does not work, and by considering recent doubt on detection of BFKL-Pomeron at finite energy (present energy region) [19], in this paper we will use the modified Pomeron model of [20] with incorporation of the Pomeron trajectories from the Donnachie and Landshoff analysis of [11, 15], to illustrate the high energy $J/\psi$-photoproduction.

In the vector dominance model, an incoming photon first converts into a vector meson which then scatters diffractively from the nucleon. Within QCD, a microscopic model of Pomeron was proposed by Donnachie and Landshoff [4], where an incoming photon first converts into a quark-antiquark pair and then exchanges a Pomeron with the nucleon. After the interaction, the quark and antiquark recombine to form the $J/\psi$ meson [3]. Here we adopt the simplified version of the DL model to define the Pomeron exchange amplitudes for $J/\psi$ photoproductions with $Q^2 = 0$ which has been verified by the nonperturbative QCD models [4, 8, 10]. In this model which reproduces rather well the vector meson photoproduction and diffractive electro-dissociation, the soft Pomeron behaves like a $C = +1$ isoscalar photon which has been justified by Landshoff and Natchmann in nonperturbative two gluon model [4]. In fact, the same suggestion has been made in [11] for the hard Pomeron. If it originates from the hard perturbative two gluon exchange, then this suggestion seems to be natural, as can be seen from the direct calculation of the corresponding loops [12]. However, for "supersoft" Pomeron, this suggestion is not self-evident. Moreover, if one assumes that it originates from the scalar meson $(f, a)$ exchange [13],
then it is more natural to consider that the corresponding effective vertices are described by an 
"effective" scalar exchange. The difference between these two different suggestions may be seen 
in polarization observables as we show below.

The DL model leads to the invariant amplitude of the \( J/\psi \) photoproduction in the form

\[
T^P_{fi} = \bar{u}_m(p') M^P_{fi} \epsilon^*_\psi \epsilon_{\gamma p} \epsilon_{m_i}(p),
\]

(2)

with

\[
M^P_{fi} = F^m_{\alpha} \Gamma^P_{n,\alpha,\mu\nu},
\]

(3)

where \( n = s, h \) and \( m \) for soft, hard and supersoft Pomeron trajectories, respectively; \( u(p) \) is 
the Dirac spinor; \( \epsilon_{\gamma p} \) and \( \epsilon_{\psi \mu} \) are the polarization vectors of the photon and the \( J/\psi \) meson, 
respectively. \( F^m_{\alpha} \) (\( n = s, h \) and \( m \)) describes the Pomeron-nucleon vertex: \( F^h,s_{\alpha} = \gamma_{\alpha}, F^m_{\alpha} = 1. \)

\( \Gamma^P_{n,\alpha,\mu\nu} \) is related to the Pomeron-\( J/\psi \) coupling [20]:

\[
\Gamma^P_{n,\nu} = \Gamma^P_{h,\nu} = g_{\alpha \nu} k^\mu - k^\alpha g_{\mu\nu}, \quad \Gamma^P_{m,\mu\nu} = (k^\mu q^\nu - k \cdot q g_{\mu\nu})/M_V,
\]

(4)

where \( k \) and \( q \) are the 4-momentum of the incoming photon and the outgoing \( J/\psi \) meson, 
respectively, and the transversality conditions \( M^P_{fi} \cdot q_{\mu} = M^P_{fi} \cdot k_{\nu} = 0 \) are fulfilled. The factor \( M^P_{fi} \) in Eq.(2) is given by the conventional Regge pole amplitude

\[
M^P_{fi} = C_{V n} F(t) F_{n}(s, t)e^{-i\pi \alpha_n(t)} \left( \frac{s - s_n}{s_0} \right)^{\alpha_n(t)}. \]

(5)

Parameter \( s_n \) is introduced to extend the standard DL-model to the low energy region. Practically 
we use the natural ”threshold” scale for this parameter: \( s_n = (M_N + M_{J/\psi})^2. \) The function \( F(t) \)
is an overall form factor [8]

\[
F(t) = F_V \cdot F_N(t),
\]

(6)

where,

\[
F_N(t) = \frac{(4M_N^2 - 2.8t)}{(4M_N^2 - t)(1 - t/0.7)^2}, \quad F_V(t) = \frac{M_V^2}{(M_V^2 - t)^2} \frac{\mu^2}{2\mu^2 + M_V^2 - t}.
\]

(7)

The constant \( C_{V n} \) is given by

\[
C_{V n} = 18 C_{0 n} s_0 \beta^2 \left( \frac{\alpha_{V \rightarrow e^+e^-}}{M_V} \right)^{1/2},
\]

(8)
with $V \equiv J/\psi$, $\beta_0 = 4$ GeV$^{-2}$, $\mu^2 = 1.1$ GeV$^2$ and the other parameters are standard. The correcting function $F_n$ in Eq. (5) is given by

$$F_n^{-2} = \frac{1}{4} \Gamma_{\mu \nu}^{a} \Gamma_{\mu' \nu'}^{a'} Tr \{ F_\alpha^n (p + M_N) F_\alpha^{a'} (p' + M_N) \} (g^{\mu \mu'} - q^{\mu} q^{\mu'}/M_N^2) g^{\nu \nu'}/4M_N^2.$$  

(9)

The corresponding Regge trajectories read

$$\alpha_h(t) = 1.418 + 0.1t, \text{ for hard Pomeron,}$$

$$\alpha_s(t) = 1.0808 + 0.25t, \text{ for soft Pomeron,}$$

$$\alpha_m(t) = 0.5475 + 0.25t, \text{ for supersoft Pomeron.}$$  

(10)

The constant factors $C_{0n}$ are chosen to reproduce $d\sigma/dt|_{t=0}$ from threshold and up to $W=100$ GeV: $C_{0s} \simeq 0.58$, $C_{0h} \simeq 0.05 C_{0s}$, $C_{0m} \simeq 0.33 C_{0s}$. The result of our fit is shown in Fig. 1, where we display differential cross section $d\sigma/dt$ as function of $W$ at $t = t_{max}$ (or $J/\psi$ production angle $\theta = 0$). Experimental data are taken from Refs. [1, 21]. The right panel shows the calculation at all available energy region. The left panel shows only the low energy region. One can see that the difference between calculations with soft and hard Pomerons alone and data at low energy is about factor of 2. Inclusion of the supersoft trajectory improves the fitting to the data. In principle, the same effect can be obtained from incorporation of the supersoft trajectory $\alpha_g(t) = -0.75 + 0.25t$ inspired by glue ball dynamics [17], though in this case we have to put the threshold parameter $s_n = 0$ and correspondingly change $C_{0n}$ in Eq.(8).

Another manifestation of the “supersoft” Pomeron may appear in the spin-density matrix elements of the $J/\psi$ decay, as described in the following.

3. The angular distribution of $J/\psi \to a + b$ is defined by

$$\frac{dN}{d\cos \Theta d\Phi} = \sum |T_{\lambda_f, \lambda_{\psi}; \lambda_i, \lambda_{\gamma}, M_{\lambda_{\psi}} (\Theta, \Phi)}|^2,$$  

(11)

where $\Theta$ and $\Phi$ are the decay and azimuthal angles of $a$ or $b$ in the rest system of the $J/\psi$ meson, respectively. For convenience, we use the Gottfried-Jackson (GJ) frame. $M_{\lambda_{\psi}}$ is the decay amplitude of the $J/\psi$ meson with helicity $\lambda_{\psi}$ and given by,

$$M_{\lambda}(\Theta, \Phi) = C \sqrt{\frac{3}{4\pi}} D^{1*}_{\lambda ab}(\Theta, \Phi, -\Theta),$$  

(12)

where $\lambda_{ab} = \lambda_a - \lambda_b$ is the helicity difference between $a$ and $b$. The constant $|C|^2$ is proportional to the decay width and if we are working with normalized angular distributions, it drops out of
the final result, and hence we can set $C = 1$. Using Eq.(12), one can express the normalized distribution in the following form,

$$\frac{dN}{d\cos \Theta d\Phi} = W(\cos \Theta, \Phi) = \frac{3}{4\pi} \sum_{\lambda \lambda_{ab}} D_{\lambda \lambda_{ab}}^{1*}(\Theta, \Phi, -\Theta) \rho_{\lambda \lambda'} D_{\lambda' \lambda_{ab}}^{1}(\Theta, \Phi, -\Theta)$$

(13)

where $\rho_{\lambda \lambda'}$ is the $J/\psi$ spin density matrix element given by

$$\rho_{\lambda \lambda'} = \frac{1}{N} \sum_{\lambda_f, \lambda_g; \lambda_i, \lambda_i'} T_{\lambda_f, \lambda_i; \lambda_g, \lambda_i'} \rho(\gamma)_{\lambda_g, \lambda_i'} T_{\lambda_f, \lambda_i; \lambda_g, \lambda_i'}$$

(14)

with the normalization factor,

$$N = \sum |T_{\lambda_f, \lambda_i; \lambda_g}|^2,$$

(15)

and $\rho(\gamma)_{\lambda, \lambda'}$ is the incoming photon density matrix. The angular distributions due to unpolarized incident photons are determined by $\rho^0_{\lambda \lambda'}$ with $\rho(\gamma)_{\lambda_g, \lambda_i'} = \delta_{\lambda_g, \lambda_i'}$. For circularly (linearly) polarized incident photons, the angular distributions are calculated from $\rho^0$ and $\rho^3(\rho^0, \rho^1$ and $\rho^2)$. For illustrating the possible manifestation of the "supersoft" trajectory, we are limited to $\rho^0$ matrix elements. The whole idea is to show how these matrix elements behave depending on the models proposed (for example, on the supersoft Pomeron model). The results for three such matrix elements are shown in Fig. 2 as function of the $J/\psi$ production angle in c.m.s. at $E_\gamma = 10$ GeV. The three models shown here are (i) the spin-conserving model, (ii) the sum of hard and soft Pomerons, (iii) the sum of hard, soft and supersoft trajectories. The case of pure scalar exchange for supersoft trajectory corresponds to the spin-conserving model, i.e. the model (i). The large difference between (ii) and (iii) suggests that this study can actually be a strong test for the existence of the supersoft Pomeron.

In summary, we have analyzed the possible manifestation of the supersoft Pomeron inspired by the scalar meson $f$, a (or glueball) exchange dynamics at low energy. We show that inclusion of this trajectory considerably improves agreement with experimental data on unpolarized cross section. Definite prediction for the spin-density matrix element has been done. However, we emphasize that the present investigation is very exploratory, owing to the lack of the precise data at low energy. It is highly desirable to obtain more data from the new facilities such as LEPS of SPring-8 in Japan and TJNAL. The polarization observables are most useful for future theoretical investigation.
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Figure captions

Fig. 1: The differential cross section $d\sigma/dt$ of $J/\psi$ photoproduction at $t = t_{\text{max}}$: (a) total available energy region, (b) low energy region. Notation: $P_s, P_h, P_m$ show the separate contributions of the soft, hard and supersoft trajectories, respectively; $P_s + P_h$ is for the coherent sum of the soft and hard Pomeron contributions, $\Sigma$ is for the coherent sum of the all Pomeron contributions.

Fig. 2: Spin-density matrix elements $\rho_{00}^0, \rho_{01}^0$ and $\rho_{11}^0$ for left, middle and left panels, respectively, as function of the $J/\psi$ production angle in c.m.s. at $E_\gamma = 10$ GeV. Notations: SS represents the prediction for the pure supersoft trajectory or the spin-conserving model, S+H is for the sum of hard and soft Pomeron, $\Sigma$ is for the total 3-Pomeron model.
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