

## Is There Window for a “Supersoft” Pomeron in $J/\psi$ Photoproduction at Low Energy?

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The low energy  $J/\psi$  photoproduction cross-section has been studied using the Pomeron model. To account for the discrepancy between experimental data and predictions of 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 a “supersoft” Pomeron, is introduced. To distinguish the conventional model from that with this new additional Pomeron, proposed observations related to other polarization observables in upcoming polarized experiments are discussed.

### §1. Introduction

It is well known that exclusive photoproduction of the light vector mesons  $\rho$ ,  $\omega$  and  $\phi$  is 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. a 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.<sup>1)</sup> Regge theory has been dominantly used to describe various aspects of high energy particle physics.<sup>2)</sup> It is considered to be applicable in the region where  $W^2$  is much greater than other variables. But surprisingly, sometimes it also works very well even at considerably smaller energies, close to the threshold.<sup>3)</sup> As stated above, the data regarding the production of light vector mesons at high energies have been well explained in this theory by the exchange of a single nonperturbative Pomeron,<sup>4)-8),10)</sup> which is known as the “soft-Pomeron”,<sup>11)</sup> with trajectory

$$\alpha_s(t) = \alpha(0) + \alpha't = 1.0808 + 0.25t. \quad (1.1)$$

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  $b = 10 \text{ GeV}^{-2}$ ), then for light vector mesons,  $\delta \simeq 0.22$  is found to be a good value to reproduce the data.

One widely discussed problem arises when this model is applied to  $J/\psi$  production at large energy for  $W > 10 \text{ GeV}$ .<sup>1)</sup> The cross-section for exclusive  $J/\psi$

production by quasi-real photons ( $Q^2 = 0$ ) at HERA is observed to increase more steeply with  $W$ . Parameterization shows that in this case  $\delta \simeq 0.8$ , in contrast to the theoretical prediction,  $\delta \simeq 0.2$ . This steep energy dependence differs greatly from the “soft” behavior of light vector mesons, and is known as the “hard” behavior of the  $J/\psi$  meson. There are two basic approaches for explaining this discrepancy: that using a perturbative two-gluon contribution<sup>12)-14)</sup> and that using the contribution of the hard Pomeron, as proposed by Donnachie and Landshoff.<sup>11)</sup>

Another problem is related to the low energy region. Previous analysis by Donnachie and Landshoff (DL) for the description of various hadronic reactions with hadrons consisting of light  $u$ ,  $d$  and  $s$  quarks shows that the low energy behavior may be successfully parameterized by a single effective Regge pole whose trajectory has the intercept  $\alpha = 0.5475$ .<sup>15)</sup> For simplicity, in this paper we call this contribution a “supersoft” trajectory or a “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 the photoproduction of the  $J/\psi$  meson, which consists of  $c$  and  $\bar{c}$  quark, and thus conventional meson exchange dynamics is forbidden, due to the OZI rule. In this case, the idea of the contribution of the additional “supersoft” Pomeron seems to be more natural. In addition to the above-mentioned DL-supersoft Pomeron, another possible contribution of the trajectory inspired by the ( $J^\pi = 0^+$ ,  $M^2 \sim 3 \text{ GeV}^2$ ) glueball predicted by lattice QCD and QCD motivated models, is also discussed in the literature.<sup>16),17)</sup> In this paper, we concentrate mainly on the subject of  $J/\psi$  photoproduction and analyze the possible manifestation of the supersoft Pomeron at low energy.

## §2. Pomeron models

The Pomeron, being a gluonic assembly, has long been established both theoretically and experimentally.<sup>18)</sup> Based on the Pomeron model, to explain the “hard” or steep  $W^2$  behavior of  $J/\psi$  photoproduction, many models have been proposed. Among these, two typical models are noteworthy: (a) the two-gluon models motivated by perturbative QCD widely discussed in the literature,<sup>12)-14)</sup> and (b) the phenomenological model motivated by non-perturbative QCD and Regge theory,<sup>11)</sup> i.e. hard Pomeron exchange with intercept 1.418. Our main interest here is the low energy region, where models of type (a) do not work, and by considering the recent doubt raised regarding detection of the BFKL-Pomeron at finite energy (the presently considered energy region),<sup>19)</sup> in this paper we use the modified Pomeron model of Ref. 20) incorporating the Pomeron trajectories from the Donnachie and Landshoff analysis of Refs. 11) and 15), to describe high energy  $J/\psi$  photoproduction.

In the vector dominance model, an incoming photon is first converted into a vector meson, which then scatters diffractively from the nucleon. Within QCD, a microscopic model of the Pomeron was proposed by Donnachie and Landshoff,<sup>5)</sup> where an incoming photon is first converted into a quark-antiquark pair and then exchanges a Pomeron with the nucleon. After this interaction, the quark and an-

tiquark recombine to form a  $J/\psi$  meson.<sup>5)</sup> Here we adopt the simplified version of the DL model to define the Pomeron exchange amplitudes for  $J/\psi$  photoproduction with  $Q^2 = 0$ , which has been verified by the nonperturbative QCD models.<sup>4),8),10)</sup> 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. This has been confirmed by Landshoff and Natchmann using a nonperturbative two-gluon model.<sup>9)</sup> In fact, the same suggestion is made in Ref. 11) for the hard Pomeron. If the hard pomeron 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.<sup>12)</sup> However, for a “supersoft” Pomeron, this suggestion is not self-evident. Moreover, if one assumes that the supersoft Pomeron originates from the scalar meson ( $f, a$ ) exchange,<sup>15)</sup> then it is more natural to believe that the corresponding effective vertices are described by an “effective” scalar exchange. The difference between the implications of these two different suggestions may be seen in the polarization observables, as we show below.

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

$$T_{fi}^{P_n} = \bar{u}_{m_f}(p') M_0^{P_n} \epsilon_{\psi\mu}^* M^{P_n\mu\nu} \epsilon_{\gamma\nu} u_{m_i}(p), \quad (2.1)$$

with

$$M^{P_n\mu\nu} = F_\alpha^n \Gamma^{P_n\alpha,\mu\nu}, \quad (2.2)$$

where  $n = s, h$  and  $m$  for soft, hard and supersoft Pomeron trajectories, respectively. Here  $u(p)$  is the Dirac spinor and  $\epsilon_{\gamma\nu}$  and  $\epsilon_{\psi\mu}$  are the polarization vectors of the photon and the  $J/\psi$  meson, respectively.  $F_\alpha^n$  ( $n = s, h$  and  $m$ ) describes the Pomeron-nucleon vertex:  $F_\alpha^{h,s} = \gamma_\alpha$ ,  $F_\alpha^m = 1$ .  $\Gamma^{P_n\alpha,\mu\nu}$  is related to the Pomeron- $J/\psi$  coupling:<sup>20)</sup>

$$\Gamma^{P_s\alpha,\mu\nu} = \Gamma^{P_h\alpha,\mu\nu} = g^{\alpha\nu} k^\mu - k^\alpha g^{\mu\nu}, \quad \Gamma^{P_m\mu\nu} = (k^\mu q^\nu - k \cdot q g^{\mu\nu})/M_V, \quad (2.3)$$

where  $k$  and  $q$  are the 4-momentum of the incoming photon and the outgoing  $J/\psi$  meson, respectively, and the transversality conditions  $M^{P_n\mu\nu} \cdot q_\mu = M^{P_n\mu\nu} \cdot k_\nu = 0$  are fulfilled. The factor  $M_0^{P_n}$  in Eq. (2.1) is given by the conventional Regge pole amplitude:

$$M_0^{P_n} = C_{V_n} F(t) F_n(s, t) e^{-i\frac{\pi}{2}\alpha_n(t)} \left( \frac{s - s_n}{s_0} \right)^{\alpha_n(t)}. \quad (2.4)$$

The 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:<sup>8)</sup>

$$F(t) = F_V \cdot F_N(t), \quad (2.5)$$

where

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

$$F_V(t) = \frac{M_V^2}{(M_V^2 - t)^2} \frac{\mu^2}{2\mu^2 + M_V^2 - t}. \quad (2.6)$$

The constant  $C_{Vn}$  is given by

$$C_{Vn} = 18 C_{0n} s_0 \beta^2 \left( \frac{\Gamma_{V \rightarrow e^+e^-}}{\alpha M_V} \right)^{1/2}, \quad (2.7)$$

with  $V \equiv J/\psi$ ,  $\beta_0 = 4 \text{ GeV}^{-2}$ ,  $\mu^2 = 1.1 \text{ GeV}^2$  as in Refs. 6) and 8) and the other parameters are standard. The correcting function  $F_n$  in Eq. (2.4) is given by<sup>20)</sup>

$$F_n^{-2} = \frac{1}{4} \Gamma_{\mu\nu}^{P_n\alpha} \Gamma_{\mu'\nu'}^{P_n\alpha'} \text{Tr}\{F_\alpha^n(\not{p} + M_N) F_{\alpha'}^n(\not{p}' + M_N)\} (g^{\mu\mu'} - q^\mu q^{\mu'} / M_{J/\psi}^2) g^{\nu\nu'} / 4M_N^2. \quad (2.8)$$

The corresponding Regge trajectories read

$$\begin{aligned} \alpha_h(t) &= 1.418 + 0.1t \quad \text{for hard Pomeron,} \\ \alpha_s(t) &= 1.0808 + 0.25t \quad \text{for soft Pomeron,} \\ \alpha_m(t) &= 0.5475 + 0.25t \quad \text{for supersoft Pomeron.} \end{aligned} \quad (2.9)$$

The constant factors  $C_{0n}$  are chosen to reproduce  $d\sigma/dt|_{t=0}$  from the threshold up to  $W=100 \text{ GeV}$ :  $C_{0s} \simeq 0.58$ ,  $C_{0h} \simeq 0.05 C_{0s}$ ,  $C_{0m} \simeq 0.33 C_{0s}$ . The result of our fit is shown in Fig. 1, where we display the differential cross section  $d\sigma/dt$  as a function of  $W$  at  $t = t_{\text{max}}$  (or the  $J/\psi$  production angle  $\theta = 0$ ). (The experimental data here are taken from Refs. 1) and 21). Here, in the low energy region (near the

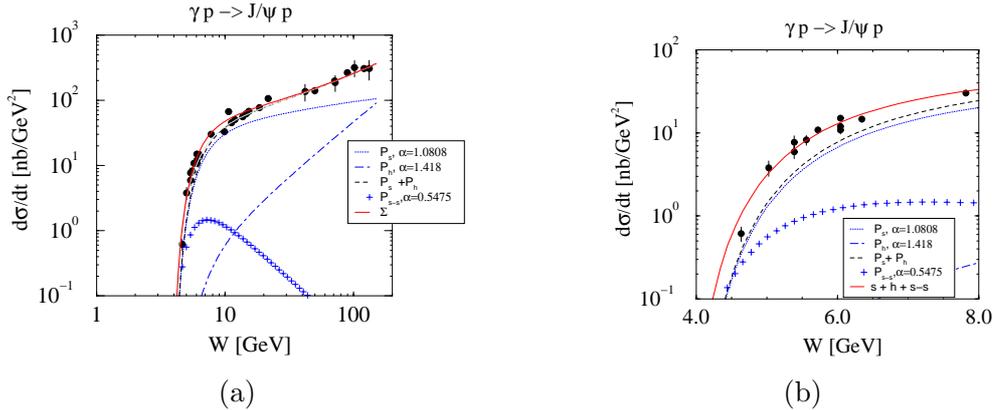


Fig. 1. The differential cross section  $d\sigma/dt$  of  $J/\psi$  photoproduction at  $t = t_{\text{max}}$ : (a) total available energy region; (b) low energy region. Here  $P_s$ ,  $P_h$  and  $P_m$  represent the separate contributions of the soft, hard and supersoft trajectories, respectively. 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

threshold), the contribution from the direct production of  $J/\psi$  has been considered to be dominant, though higher states (2S, P) may contribute substantially at high energies. The left panel displays the calculation for all available energy regions. The right panel shows only the low energy region. One can see that there is a gap of about a factor 2 between the calculations with soft and hard Pomerons alone and the data at low energy. Inclusion of the supersoft trajectory improves the fit 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 glueball dynamics,<sup>17)</sup> though in this case we have to set the threshold parameter as  $s_n = 0$  and correspondingly change  $C_{0n}$  in Eq. (2.7).

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. Density matrix elements of the $J/\psi$ meson

The angular distribution of  $J/\psi \rightarrow a + b$  is defined by<sup>22)</sup>

$$\frac{dN}{d \cos \Theta d\Phi} = \sum |T_{\lambda_f, \lambda_\psi; \lambda_i, \lambda_\gamma} \cdot M_{\lambda_\psi}(\Theta, \Phi)|^2, \quad (3.1)$$

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 is given by

$$M_\lambda(\Theta, \Phi) = C \sqrt{\frac{3}{4\pi}} D_{\lambda\lambda_{ab}}^{1*}(\Theta, \Phi, -\Theta), \quad (3.2)$$

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. (3.2), one can express the normalized distribution in the form

$$\frac{dN}{d \cos \Theta d\Phi} = W(\cos \Theta, \Phi) = \frac{3}{4\pi} \sum_{\lambda\lambda_{ab}} D_{\lambda\lambda_{ab}}^{1*}(\Theta, \Phi, -\Theta) \rho_{\lambda\lambda'} \rho_{\lambda'\lambda_{ab}}^1(\Theta, \Phi, -\Theta), \quad (3.3)$$

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

$$\rho_{\lambda\lambda'} = \frac{1}{N} \sum_{\lambda_f, \lambda_\gamma; \lambda_i, \lambda'_\gamma} T_{\lambda_f, \lambda; \lambda_i, \lambda_\gamma} \rho(\gamma)_{\lambda_\gamma \lambda'_\gamma} T_{\lambda_f, \lambda'; \lambda_i, \lambda'_\gamma}, \quad (3.4)$$

with the normalization factor

$$N = \sum |T_{\lambda_f, \lambda; \lambda_i, \lambda_\gamma}|^2, \quad (3.5)$$

and  $\rho(\gamma)_{\lambda_\gamma \lambda'_\gamma}$  is the incoming photon density matrix. The angular distributions due to unpolarized incident photons are determined by  $\rho_{\lambda, \lambda'}^0$  with  $\rho(\gamma)_{\lambda_\gamma \lambda'_\gamma} = \delta_{\lambda_\gamma \lambda'_\gamma}$ .

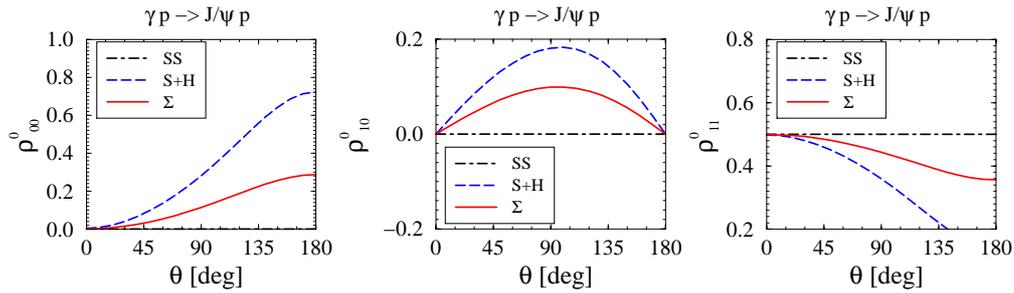


Fig. 2. Spin-density matrix elements  $\rho_{00}^0$ ,  $\rho_{01}^0$  and  $\rho_{11}^0$  are displayed in the left, middle and right panels, respectively, as functions of the  $J/\psi$  production angle in the c.m.s. at  $E_\gamma = 10$  GeV. Here SS represents the prediction for the pure supersoft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

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, the supersoft Pomeron model). The results for three such matrix elements are shown in Fig. 2 as functions of the  $J/\psi$  production angle in the c.m.s. at  $E_\gamma = 10$  GeV. The three models considered here are (i) the spin-conserving model, (ii) the sum of hard and soft Pomerons, and (iii) the sum of hard, soft and supersoft trajectories. The case of pure scalar exchange for supersoft trajectories corresponds to the spin-conserving model, i.e. model (i). The large difference between the results of (ii) and (iii) suggests that this study can actually be a strong test for the existence of the supersoft Pomeron.

#### §4. Conclusion and discussion

Summarizing, we have analyzed the possible manifestation of the inclusion of the supersoft Pomeron inspired by the scalar meson  $f$ ,  $a$  (or glueball) exchange dynamics at low energy. We have shown that inclusion of this trajectory considerably improves agreement with experimental data on the unpolarized cross section. Though we have discussed only  $J/\psi$  production in this paper, the production of  $\psi'$  and  $\Upsilon$  is also interesting processes for testing the supersoft Pomeron effect. The need for the supersoft Pomeron to explain these data will indeed be a good proof of its existence. We hope there will be more data in the future for analysis. A definite prediction for the spin-density matrix element has also been made. However, we emphasize that the present investigation is very exploratory, owing to the lack of precise data at low energy. It is highly desirable to obtain more data from 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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