

\textbf{Abstract}

Within the framework of QED we investigate the inclusive $J/\psi$ production at $e^+e^-$ colliders. It is expected to be as a further test to the charmonium production mechanisms and QED. We find that at the energies of CESR, BEPC, and TRISTAN (e.g. $4.0\text{GeV} \leq \sqrt{s} \leq 60\text{GeV}$), the contributions of the concerned electromagnetic processes to the $J/\psi$ inclusive production are great, even dominant, thus they greatly affect the observation of the color-octet $J/\psi$ production signature at $e^+e^-$ colliders. The production of $\psi'$, being similar to that of $J/\psi$'s, is roughly estimated, and its influence on the observation of the color-octet $J/\psi$ production signature in $e^+e^-$ collision is also discussed.

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Since $J/\psi$ was discovered, the issues on its production has constantly drawn a lot of attention from both theorists and experimentalists, especially after several important progresses being made recently. The first is about the calculation of the fragmentation functions of a parton evolving into a heavy meson (heavy quarkonia or $B_c$ meson) in the framework of perturbative QCD [1]. The second comes from the comparison of the theoretical predictions, which are achieved due to the calculations of the fragmentation functions, with the experimental data of the $J/\psi$ and the $\psi'$ prompt production [2]. As a result of the comparison, a disparity between the theoretical predictions and the Tevatron experimental data, the so-called ‘$\psi'$($\psi$) surplus’ problem, is found [3]. The third advancement is the advent of a plausible and interesting suggestion, the so-called ‘color-octet mechanism’ in quarkonium production [4], in solving this puzzle. To confirm the color-octet mechanism further, several suggestions have been proposed. Many a kind of production processes of the $J/\psi$ production in colliders are investigated by groups [5–12]. Among them the $J/\psi$ inclusive production in $e^+e^-$ annihilation has received special and broad interests [11]. Being one of the best grounds to observe the color-octet signature because of the clean background, $e^+e^-$ collider facilities are emphasized by the authors [11–13]. Whereas, we find that there are two kinds of $J/\psi$ production processes in $e^+e^-$ collision, i.e., i) the scattering production $e^+e^- \rightarrow e^+e^- + J/\psi$ (we will refer this kind of $J/\psi$ production as scattering production later on in this paper) depicted as the Feynman diagrams Figs.1.a, 1.b. ii) the hard-photon-associated production $e^+e^- \rightarrow J/\psi + \gamma$ (we will refer this kind of $J/\psi$ production as hard-photon production later on in this paper) depicted as Feynman diagrams Fig.1.c, are overlooked in literatures, which have certain degrees of influence on the conclusions of the previous work. Recently the hard-photon production $e^+e^- \rightarrow J/\psi + \gamma$ in the $e^+e^-$ annihilation was computed, and we found in that paper that this kind of process indeed has a great influence on the observation of the color-octet signature at $e^+e^-$ colliders [14]. Furthermore, we believe it is meaningful to consider these two kinds of $J/\psi$ production processes (scattering and hard-photon production) together in detail to give a more complete estimation about their effects on the observation of the color-octet signature. Although there are still other kinds of $J/\psi$ production processes left unconsidered in $e^+e^-$ annihilation, however, they are expected to be neither as great nor as important as the scattering one in affecting the observation of the color-octet signature. e.g., $e^+e^- \rightarrow J/\psi + f + \bar{f}$, where $f, \bar{f}$ denote a pair of quark and anti-quark or lepton and anti-lepton except for a pair of electron and positron,
is similar to the scattering production process $e^+ + e^- \rightarrow e^+ + e^- + J/\psi$ at the first glance, whereas in fact they are much different. The former, being always through $e^+ e^-$ s-channel annihilation, suffers from the s-channel suppression due to the annihilation, especially when the collision energy increased to a certain scale. Therefore, We will not discuss these kinds of production here, but leave them to a later analysis elsewhere [15].

Theoretically, from Figs.1.a-1.c it is easy to see that the corresponding processes are of QED nature. A common features of them is that there is always a virtual photon coupling to an electron in relevant diagrams, which stands as the photon in the $J/\psi$ resonance. Thus, except for the non-perturbative QCD factor, the processes are of the pure QED. It is this reason that we call this two kinds of $J/\psi$ production as the electromagnetic production. And because of their this kind of character they may be computed reliably and precisely to any given order in $\alpha$. Note that for simplicity, only the typical Feynman diagrams for the $J/\psi$ electromagnetic production is presented here. Of the scattering production processes of $e^+ e^- \rightarrow e^+ e^- + J/\psi$ depicted as Fig.1.a and Fig.1.b, the later diagram (and the other similar ones which are not shown) contains a exchanged photon and an electron (or positron) in t-channel, thus the diagram is expected to contribute a dominant fraction to the cross section. Especially, in the area of the phase-space where the momenta of the exchanged photon and the electron approach to their mass shells, respectively. The hard-photon production, with the character of a hard photon emitting from the electron line and the $J/\psi$ coupling to the electron line through a virtual photon as well, is depicted as Fig.1.c. It is of order $O(\alpha^3)$ in QED coupling constant, i.e., one order lower than that of scattering ones. Besides, because there is an exchanged electron (or positron) in t-channel as well, it will make a great contribution in the $J/\psi$ production.

Because of the concerned energy scales here are comparatively rather ‘low’, which may even comparable to $m_{J/\psi}$, the so-called electromagnetic fragmentation approach (EMFA) is not applicable. The EMFA works well at much high energies ($\sqrt{s} \gg m_{J/\psi}$). In addition, if one adopts the electromagnetic fragmentation approach here regardless of whether it is suitable or not, it seems to be no advantages in simplifying the calculation of the processes. Therefore, all the results in this paper come from a full QED calculation rather than EMFA approach.

The electromagnetic production processes emphasized here are all in color-singlet production mechanism, therefore, at various energies of present available collider facilities, such as TRISTAN, CESR and BEPC, to calculate the processes precisely is meaningful to
the study of the color-octet production mechanism. On the other hand, the estimation of
the $J/\psi$ electromagnetic production may play a role in further testing the applicability of
the QCD in lower energy region like $m_{J/\psi}$ or so. Hence, to make a thoroughly discussion
on the $J/\psi$ electromagnetic production is needed.

The $J/\psi$ production cross section of the hard-photon process can be calculated
straightforward making use of the standard formalism [14]. The differential cross
section can be expresses as:

$$\frac{d\sigma}{dt} = \frac{32\pi\alpha^3|R_S(0)|^2}{3M^3s^2}\left[\frac{2M^2s}{tu} + \frac{t}{u} + \frac{u}{t}\right], \quad (1)$$

where $M$ is the mass of charmonium; $\alpha$ is electromagnetic coupling constant; $s = (p_1 + p_2)^2$; $t = (k - p_1)^2$; $u = (P - p_1)^2$. For simplicity, the eq.(1) is a result of throwing away
the electron mass, while in doing numerical calculations the mass will be kept. As the
radial wave function at the origin $|R_S(0)|^2$ here is exactly equal to that appearing in the
Corresponding equation of $J/\psi \rightarrow e^+e^-$, i.e.

$$\Gamma(J/\psi \rightarrow e^+e^-) = \frac{4\alpha^2}{M^2}|R_S(0)|^2, \quad (2)$$

we will determine it from the experimental value of the decay width of $J/\psi$ to lepton pair.
This procedure provides all of the theoretical corrections to the wave function at origin
being included.

The differential cross section versus $t$, hence the angular $\cos \theta$, at a given CMS energy
is

$$\frac{d\sigma}{dt} = \frac{6\pi\alpha \Gamma_{exp}(J/\psi \rightarrow e^+e^-)}{M^2} \left[\frac{2M^2s}{tu} + \frac{t}{u} + \frac{u}{t}\right]. \quad (3)$$

Therefore,

$$\frac{d\sigma}{d\cos \theta} = \frac{6\pi\alpha \Gamma_{exp}(J/\psi \rightarrow e^+e^-)s}{M(1 - r)\sin^2 \theta} \left[(1 + r)^2 + (1 - r)^2 \cos^2 \theta\right], \quad (4)$$

where $r \equiv M^2/s$.

The analytical formulae of the cross section of scattering production processes are
complicated and hence are not suitable to list here. In fact, in doing the numerical
calculations, we have used our computer programme code. And to test its reliability we
have compared some results of using programme code with that using the full analytical
formulae. The value of the wave function at the origin used in these processes take the same as that in the hard-photon production.

The total cross sections for various kinds of the \( J/\psi \) production processes in \( e^+e^- \) collision are plotted in Fig.2. As pointed out above, for we are also interested in seeing the influence of the \( J/\psi \) electromagnetic production on the observation of the color octet signature through detecting the inclusive \( J/\psi \) production, in Fig.2 we show a comparison of the contributions of the \( J/\psi \) electromagnetic production with that of the color-octet ones depicted as Fig.1.d and the color-singlet one as Fig.1.e, which have been studied and stresses in Refs. [12][13][8]. In this paper, the corresponding results are obtained directly from those references.

As discussed above, of the scattering production, the relevant Feynman diagrams may be divided into two sub-groups: one always contains an \( e^+e^- \) annihilation (Fig.1.a) and the other always contains a t-channel exchange of a photon (Fig.1.b). For the processes containing a exchanged photon in t-channel we will call it as the ‘scattering group’ in this paper. It is easy to check that each group itself is gauge invariant. To see the different contributions from each group, in Fig.3 we plot the cross section not only for each sub-group, but also for the total as well. From Fig.3 one can see obviously that the scattering sub-group’s contribution to \( J/\psi \) production is dominant over the other. With the same reason, the scattering production will be the greatest one among various kinds of production processes at high energies, although it is at least one order higher in \( \alpha \) than most of the others. The similar production process \( e^+e^- \rightarrow J/\psi + f\bar{f} \) \((f \neq e)\), as discussed above, containing the Feynman diagrams of the type of Fig.1.a only, is expected to have a contribution minor to that of the scattering one’s to the inclusive \( J/\psi \) production in \( e^+e^- \) annihilation.

The differential cross sections of \( d\sigma/d\cos \theta \) of different processes as shown in Fig.1 are plotted in Figs.4.a-4.c, where the \( \theta \) denotes the angle between the direction of the produced \( J/\psi \) with the colliding beam. The CMS energies are taken the ones of the colliders BEPC, CESR and TRISTAN, respectively. In order to see the dependent behavior of the differential cross section of the \( J/\psi \) production on the energy more precisely, the curves for the differential cross sections at several energies are plotted in Fig.5.

Actually, a complete set of the Feynman diagrams should contains \( Z \)-boson-exchange ones in replacing of the virtual photon in each diagram of Figs.1.a -1.e. Whereas at low energies, such as at BEPC, CESR, even TRISTON, where \( \sqrt{s} < m_Z \), all the contributions
from the $Z$-boson-exchange diagrams are small, thus, can be neglected. At high energies, e.g., equal or higher than that of LEP-I, the propagator of the virtual $Z$ boson may approach or overtake its mass pole, while the contribution from the $Z$ boson exchange may becomes great. Therefore we cannot always overlook them without a careful study. To show the virtual $Z$ effect, we have included this kind of contribution in our numerical calculations, which can be seen as a peak in Fig.3 around the energy of $Z$ resonance. In general at such a high energy, many complicated $J/\psi$ production channels may be open, therefore, more detailed investigations are still needed. At present, we only restrain ourselves to a relatively low energy situation.

From Fig.2, one can see that the contribution from the scattering production at comparatively high energies and that from the hard-photon production at comparatively low energies are dominant among all kinds of the considered production processes. Furthermore from Figs.4.a-4.c one may see the fact that the $J/\psi$ electromagnetic production has the common features that the differential cross section of the production approaches to the maximum when the produced $J/\psi$ approaches to the beam direction, but it is still significant when the produced $J/\psi$ at large $P_T$. This is due to the fact that both cases are dominated by t-channel exchange diagrams. The produced $J/\psi$ in the hard-photon and the scattering processes, the former at comparatively low energies and the later at comparatively high energies, in the direction perpendicular to that of the beams still contributes such a fraction that is not much smaller than the greatest one of the considered ‘others’, no matter the greatest one of the considered ‘others’ is alternated with the change of the CMS energy. For instance, the contribution of the color-singlet one corresponding to the Feynman diagram Fig.1.e is smaller than those of the color-octet ones corresponding to the Feynman diagram Fig.1.d in the energy region $\sqrt{s} \leq 12 GeV$, while the situation will be converse in the energy region $\sqrt{s} \geq 12 GeV$. Moreover, it should be noted that the hard-photon and the scattering $J/\psi$ production have a similar angular distribution in shape as the color-octet $J/\psi$ production, whereas, the shape is emphasized as the peculiar character of the produced $J/\psi$ in color-octet processes in detecting the color-octet signature $[11]$. In showing the energy dependence, the total cross sections versus the CMS energies for various kinds of production processes, the Fig.2 is depicted. Considering the fact that it is impossible to measure either the hard photon or the pair of $e^+e^-$ when they approach to beam direction, we plot two curves in Fig.2 for each of the scattering process. One
with a cut on the outgoing angular of $J/\psi$ and the other without any cut. From Fig.2 one may see obviously the difference of the one without a cut with the one with a cut of $20^0 \leq \theta \leq 160^0$ on the angular between the direction of beam and that of the produced $J/\psi$.

For $\psi'$ production, each of the processes having contributions to the $J/\psi$ production will do for $\psi'$. The $\psi'$, being a radial excited state of $J/\psi$, has the same quantum numbers as that of $J/\psi$ in the non-relativistic limit. Moreover, because the $J/\psi$ electromagnetic production has a common features, i.e. the $J/\psi$ always couples to a charged fermion line through a virtual photon, we must have a very similar result for the $\psi'$ electromagnetic production with the same types of the Feynman diagrams as Figs.1.a-1.c. The difference of the electromagnetic production of these two mesons exist only in the values of wave function at origin and the slightly different masses. It is well known that the squared absolute values of the wave function at the original of $J/\psi$ and $\psi'$ are different roughly by a factor 2. Therefore, the rate of the $\psi'$ electromagnetic production is roughly equal to one half of that of the $J/\psi$ electromagnetic production under non-relativistic limit. As the branching ratio of the decay $\psi' \rightarrow J/\psi + \cdots$ is quite great, $\sim 57\%$, in $e^+e^-$ collision the signal of the $\psi'$ production with a prompt cascade decay to $J/\psi$ may generate an event pattern, which looks like as that of the direct color-octet $J/\psi$ production or of the direct color-singlet $J/\psi$ production very much. Thus, the $\psi'$ production and then decay into $J/\psi$ will also disturb the detection to the color-octet $J/\psi$ production signature in a certain degree.

In our calculations, the input parameter values are [8,12,18]

\[
\alpha_s(2m_c) = 0.28, \quad \alpha_{EM}(2m_c) = 0.0075, \quad m_c = 1.48 \text{ GeV}, \quad m_c = 0.51 \text{ MeV},
\]

\[
\Gamma_{ee} = 5.26 \pm 0.37 \text{ keV}, \quad <0|O_1^{J/\psi}(^3S_1)|0> = 1.2 \text{ GeV}^3,
\]

\[
\frac{<0|O_0^{J/\psi}(^1S_0)|0>}{3} + \frac{<0|O_8^{J/\psi}(^3P_0)|0>}{m_c^2} = (2.2 \pm 0.5) \times 10^{-2} \text{ GeV}^3, \quad (5)
\]

which are widely used in literatures. However, it should also be noted here that the input values of the color-octet matrix elements come from the fitting procedure of the Non-relativistic QCD (NRQCD) [17] calculation [3] with the Tevatron data [2]. The obtained value there are not fully consistent with other determinations by fitting to dif-
ferent experimental data, and it appears to be overestimated. Moreover, in calculating the color-octet $J/\psi$ production processes $[11]$, both the values of $<0|\mathcal{O}^{J/\psi}_{8}(1S_0)|0>$ and $<0|\mathcal{O}^{J/\psi}_{8}(3P_0)|0>$ have taken the maximum, therefore, the estimations for the color-octet production are probably also overestimated.

In conclusion, the $J/\psi$ electromagnetic production, the hard-photon production and the scattering production, in $e^+e^-$ collision is an interesting and important issue, not only because it has been less considered so far, but also because it possesses distinctive significance to the study of quarkonium physics. It has a different character with the ones depicted as Feynman diagrams Figs.1.d and Figs.1.e. The electromagnetic production is dominantly through the $t$-channel exchange, but the ‘others’ are through $s$-channels. In addition, what we would like to emphasized here is that the hard-photon production may be used in experiment to test the QCD calculations and the quarkonium production mechanism, if experimentally the hard photon can be identified well, i.e. the process can be measured exclusively. Even, this process may be uses in calibrating the detector for the relevant experiments, because $\alpha$ is smaller enough to provide a reliable perturbative calculation. Moreover, if experimentally the final $e^+e^-$ pair (not from the $J/\psi$ decay) in the process $e^+e^- \rightarrow e^+e^-+J/\psi$ may be observed exclusively, the process may also be used to play the same role as what hard-photon process do. If one would like, as suggested by $[11]$, to observe the signature of the color-octet mechanism in $e^+e^-$ annihilation merely through the inclusive $J/\psi$ production at comparatively low energies facilities, such as those of BEPC, CESR and TRIESTON, one has to take into account the contribution of the electromagnetic production of not only the $J/\psi$ but also $\psi^\prime$. One should take that part of events as the background of the color-octet signature’s in the $J/\psi$ inclusive production. In principle, this may be practicable. In practice, it needs a precisely exclusive measurement of the $J/\psi$ production in order to distinguish the color-octet signature from the background presented here. In all, there should be more investigations on the quarkonium production, even in the electron-positron collision.

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FIGURE CAPTIONS

Fig.1: The typical Feynman diagrams of the concerned $J/\psi$ production color-singlet and color-octet processes in electron-positron collision. a) One-t-channel scattering process of $e^+e^- \rightarrow e^+e^- + J/\psi$; b) Two-t-channel scattering process of $e^+e^- \rightarrow e^+e^- + J/\psi$; c) The hard-photon process of $e^+e^- \rightarrow \gamma + J/\psi$ with an electron exchange in t-channel; d) The color-octet $J/\psi$ production processes of $e^+e^- \rightarrow g + J/\psi$; e) The traditional color-singlet $J/\psi$ production process of $e^+e^- \rightarrow g + g + J/\psi$.

Fig.2. The total cross sections of the $J/\psi$ production versus the CMS energy $\sqrt{s}$ of various processes.

Fig.3 The total cross sections for the $J/\psi$ production process $e^+e^- \rightarrow e^+e^- + J/\psi$. The thin solid line illustrates the summed cross section; the dashed-dotted line depicts that with a cut $20^\circ \leq \theta \leq 160^\circ$ in angle; the dashed line denotes the contribution only from the Feynman diagrams Fig.1a; the dotted line denotes the contribution from Feynman diagrams Fig.1b.

Fig.4: Fig.4.a. The differential cross sections $d\sigma/d\cos\theta$ of the $J/\psi$ production for the various processes at the CMS energy $\sqrt{s} = 4.03\text{GeV}$ (BEPC). Fig.4.b. The differential cross sections $d\sigma/d\cos\theta$ of the $J/\psi$ production for the various processes at the CMS energy $\sqrt{s} = 10.6\text{GeV}$ (CESR). Fig.4.c. The differential cross sections $d\sigma/d\cos\theta$ of the $J/\psi$ production for the various processes at the CMS energy $\sqrt{s} = 64.0\text{GeV}$ (TRISTAN).

Fig.5 The differential cross sections $d\sigma/d\cos\theta$ of the $J/\psi$ electromagnetic production at different CMS energy.
\[ \sigma(e^+e^- \rightarrow e^+e^- J/\psi) \]
\[ \sigma(e^+e^- \rightarrow e^+e^- J/\psi, 160^\circ > \theta > 20^\circ) \]
\[ \sigma(e^+e^- \rightarrow \gamma J/\psi) \]
\[ \sigma(e^+e^- \rightarrow g + J/\psi) \]
\[ \sigma(e^+e^- \rightarrow g + S_0^{[8]} ) \]
\[ \sigma(e^+e^- \rightarrow g + P_2^{[8]} ) \]
\[ \sigma(e^+e^- \rightarrow g g + J/\psi) \]

**Fig. 2**
\[
\sigma(e^-e^+ \rightarrow e^-e^+ J/\psi)
\]

Fig. 1(a)

\[
\sigma(e^-e^+ \rightarrow e^-e^+ J/\psi (Fig.1b))
\]

\[
\sigma(e^-e^+ \rightarrow e^-e^+ J/\psi, 160^\circ > \theta > 20^\circ)
\]

\[
\sqrt{s} (GeV)
\]

Fig. 3
\[ \frac{d\sigma}{d\cos\theta_{J/\psi,\text{beam}}} \] 

\[ \sigma(e^-e^+ \rightarrow \gamma J/\psi) \]

\[ \sigma(e^-e^+ \rightarrow g + ^1S^0_p) \]

\[ \sigma(e^-e^+ \rightarrow g + ^3P_J^0) \]

\[ \sigma(e^-e^+ \rightarrow g g + J/\psi) \]

\[ \sigma(e^-e^+ \rightarrow e^-e^+ + J/\psi) \]

Fig. 4.a
\[ \sigma(e^-e^+ \rightarrow J/\psi) \]
\[ \sigma(e^-e^+ \rightarrow g + \gamma J/\psi) \]
\[ \sigma(e^-e^+ \rightarrow g + 1S_0^{[8]} \]
\[ \sigma(e^-e^+ \rightarrow g + 3P_1^{[8]} \]
\[ \sigma(e^-e^+ \rightarrow g + g + J/\psi) \]
\[ \sigma(e^-e^+ \rightarrow e^-e^+ + J/\psi) \]

Fig. 4.b
Fig. 4.c

\[ \frac{d\sigma}{dcos\theta}(\text{pb}, \sqrt{s} = 60 \text{ GeV}) \]

\[ \sigma(e^+e^+ \rightarrow \gamma J/\psi) \]
\[ \sigma(e^+e^+ \rightarrow g + ^1S_0^{[8]}) \]
\[ \sigma(e^+e^+ \rightarrow g + ^3P_J^{[8]}) \]
\[ \sigma(e^+e^+ \rightarrow g g + J/\psi) \]
\[ \sigma(e^+e^+ \rightarrow e^+e^+ + J/\psi) \]
Fig. 5

\begin{align*}
\sigma(e^+e^- \rightarrow e^+e^- J/\psi(4.03 GeV)) \\
\sigma(e^+e^- \rightarrow e^+e^- J/\psi(10.6 GeV)) \\
\sigma(e^+e^- \rightarrow e^+e^- J/\psi(60 GeV)) \\
\sigma(e^+e^- \rightarrow e^+e^- J/\psi(91 GeV))
\end{align*}