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J/ψ production in top quark decays

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We calculate the direct production rate of J/ψ in top quark decays. The color-octet J/ψ production via $t \to W^+ b J/\psi$ is shown to have a large branching ratio of order 1.5×10^{-4}, which is over an order of magnitude higher than that of the color-singlet J/ψ production via $t \to W^+ b J/\psi gg$ or $t \to W^+ b \chi_{cJ} g$ followed by $\chi_{cJ} \to J/\psi\gamma$. Our result can also be used as a tool to test the importance of the color-octet mechanism in heavy quarkonium production in the future. [S0556-2821(97)02203-0]

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Since the discovery of charmonium in 1974, there have been a lot of attempts to interpret the production and decays of these new bound states. Among many scenarios, the color-singlet model [1] gains more success than other alternatives [2] such as the color-evaporation model [1,3]. Based upon the color-singlet model, it is possible to calculate the production rates of heavy quarkonium from first principles by standard methods [4]. Indeed, the study of heavy quarkonium production provides a suitable ground to precisely test quantum chromodynamics (QCD).

However, during the past few years, it was found that the color-singlet model also has some defects in describing the production of heavy quarkonium [5]. Predictions for S-wave charmonium, J/ψ and ψ', production failed to explain the new data of the Collider Detector at Fermilab (CDF) at the Tevatron [6]. To resolve these discrepancies one needs to seek new production mechanisms as well as a new paradigm for treating heavy quark-antiquark bound systems that go beyond the color-singlet model. To these ends, recently a novel effective field theory for bound states of heavy quarks and antiquarks was provided by Bodwin, Braaten, and Lepage [7] in the context of nonrelativistic quantum chromodynamics (NRQCD). In this new framework a heavy quarkonium state H is not solely regarded as simply a quark-antiquark pair but rather a superposition of a series of Fock states:

$$\begin{aligned}|H(nJ^{PC})\rangle = {} & O(1)\times|Q\overline{Q}(^{2S+1}L_J,\underline{1})\rangle \\ & + O(v)|Q\overline{Q}(^{2S+1}(L\pm1)_{J'},\underline{8})\rangle \\ & + O(v^2)|Q\overline{Q}(^{2S+1}L_J,\underline{8}\ \text{or}\ \underline{1})gg\rangle + \cdots,\end{aligned} \tag{1}$$

where the angular momentum of the $Q\overline{Q}$ pair in each Fock state is labeled by $^{2S+1}L_J$ with a color configuration of either $\underline{8}$ or $\underline{1}$. The pure $Q\overline{Q}$ state in the color-singlet model is only the leading term in the above expansion. Up to and including $O(v^2)$ in the Fock state expansion in describing $J/\psi(\psi')$ production, the color-octet matrix element $\langle\mathcal{O}_8^{J/\psi}(^3S_1)\rangle[\langle\mathcal{O}_8^{\psi'}(^3S_1)\rangle]$ should also be taken into consideration. Although these color-octet matrix elements are suppressed by order of v^4 relative to the corresponding color-singlet matrix elements $\langle\mathcal{O}_1^{J/\psi}(^3S_1)\rangle[\langle\mathcal{O}_1^{\psi'}(^3S_1)\rangle]$ from the nonrelativistic QCD (NRQCD) ''velocity scaling rules,'' they are enhanced by a factor of $1/\alpha_s^2$ relative to the color-singlet processes in short-distance perturbative calculations. Therefore, the suppression in the color-octet matrix elements can be compensated. Treating the color-octet matrix elements as free parameters, the description of high-P_T $J/\psi(\psi')$ production at the Tevatron can indeed be rescued [8–10].

Recently, from a direct search at the Tevatron, the CDF and D0 groups confirmed the existence of a heavy top quark [11,12], with a mass of $(176\pm8\pm10)$ GeV or $(199^{+19}_{-21}\pm22)$ GeV. The next experimental studies will focus on the determination of its properties. Among others, the measurement of top quark decays into heavy quark mesons which are made of charm or bottom quarks and antiquarks will be of special interest. In particular, the charmonium production in top quark decays will provide very useful information in testing the standard model.

In this paper we would like to discuss the direct (prompt) production of J/ψ in top quark decays. This type of production differs from the indirect J/ψ production processes which mainly come from $t\to W^+b$ followed by b decays. Although the direct production rate is smaller than that from b decays, they can be well distinguished experimentally from each other by using the vertex detector. In fact, direct charmonium production has been extensively studied at the Tevatron.

Since in the standard model the main decay mode of the top quark is $t\to W^+b$, the dominant direct J/ψ production is expected to proceed via $t\to W^+bg^*$ with the virtual gluon g^* fragmenting into charmonium. In this paper we consider three subprocesses for J/ψ production via $t\to W^+bg^*$: (i) color-octet gluon fragmentation $g^*\to J/\psi$, (ii) color-singlet gluon fragmentation $g^*\to J/\psi gg$, and (iii) color-singlet gluon fragmentation $g^*\to\chi_{cJ}g$ followed by $\chi_{cJ}\to J/\psi\gamma$, where χ_{cJ} $(J=0,1,2)$ are the charmonium P-wave states.

Direct charmonium production appears at orders α_s^4 or over in the color-singlet model [13], whereas the color-octet production process given by $t\to W^+bJ/\psi$, as shown in Fig. 1, is at order α_s^2. The amplitude of the latter process may be written as

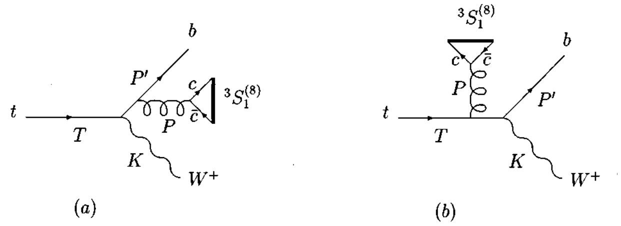

FIG. 1. Color-octet charmonium production process in top quark decays.

$$\mathcal{A}(t\to W^+ bJ/\psi)=\frac{igg_s^2V_{tb}}{2\sqrt{2}M}T^a\epsilon^\mu_\psi\epsilon^\alpha_W\overline{u}(P')$$

$$\times\left[\gamma_\mu\frac{1}{\not P'+\not P-m_b}\gamma_\alpha(1-\gamma_5)\right. \tag{2}$$

$$\left.+\gamma_\alpha(1-\gamma_5)\frac{1}{\not P'+\not K-m_t}\gamma_\mu\right]$$

$$\times u(T)\mathcal{M}_8(J/\psi), \tag{3}$$

where T, P', K, and P are the four-momenta of the top quark, b quark, W^+ boson, and J/ψ, respectively, and $\mathcal{M}_8(J/\psi)\equiv|\mathcal{A}(Q\overline{Q}[^3S_1^{(8)}]\to J/\psi)|$ is the long-distance nonperturbative amplitude of all possible way of evolving to J/ψ starting from a color-octet $Q\overline{Q}[^3S_1^{(8)}]$ pair at short distances. It may be treated as phenomenological parameter which can be determined by fitting the data, e.g., from the J/ψ production rate at the Tevatron. We define

$$f_1=-(M^2+2m_t^2)[(m_t^2-m_b^2)^2+(m_t^2+m_b^2-2m_w^2)m_w^2],$$

$$f_2=-2(m_t^2-m_b^2)^2(M^2+m_b^2+m_t^2)$$
$$+2m_w^2[(2M^2+3m_w^2)(m_b^2+m_t^2)$$
$$-2(M^2+m_w^2)^2-4m_b^2m_t^2],$$

$$f_3=-m_b^2-m_t^2-2m_w^2,$$

$$f_4=2m_b^4-4m_b^2m_t^2+2m_t^4-4M^2m_w^2+2m_b^2m_w^2+2m_t^2m_w^2$$
$$-4m_w^4,$$

$$f_5=-(M^2+2m_b^2)[(m_t^2-m_b^2)^2+(m_t^2+m_b^2-2m_w^2)m_w^2],$$

$$f_6=2(m_t^2-m_b^2)^2-2(2M^2-m_b^2-m_t^2+2m_w^2)m_w^2,$$

$$f_7=-2m_b^2-2m_t^2,\quad f_8=-m_b^2-m_t^2-2m_w^2,$$

where $M=2m_c$ is the mass of J/ψ. Then, the differential decay rate for $t\to W^+bJ/\psi$ is given by

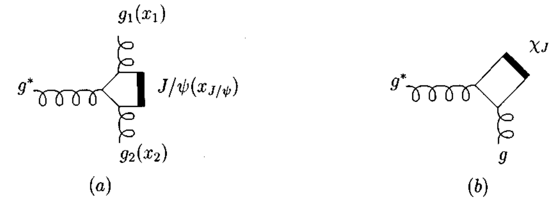

FIG. 2. Diagrams for color-singlet J/ψ production (a) via $g^*\to J/\psi gg$ and (b) via $g^*\to\chi_{cJ}g\to J/\psi\gamma g$. For diagram (a) $x_i\equiv 2E_i/\mu$ with $i=J/\psi$, and g_1,g_2 are the energy fractions carried by the decay products in g^* rest frame normalized to $\mu\equiv m(g^*)$.

$$\frac{d^2\Gamma}{dx_1dx_2}(t\to W^+bJ/\psi)$$
$$=\frac{g^2\alpha_s^2|V_{tb}|^2|\mathcal{M}_8(J/\psi)|^2}{24\pi M^2m_t^3m_w^2}\{f_1x_1^2+f_2x_1x_2+f_3x_1^3x_2$$
$$+f_4x_1^2x_2+f_5x_2^2+f_6x_1x_2^2+f_7x_1^2x_2^2$$
$$+f_8x_1x_2^3\}/(x_1^2x_2^2). \tag{4}$$

Here, the variables $x_1=m_b^2-m_t^2-m_w^2+2m_tE_w$. The physical limits of x_1 and x_2 are

$$x_1^\pm=\frac{1}{2(m_t^2-x_2)}\{(M^2-x_2)(m_t^2+m_b^2-m_w^2-x_2)$$
$$\pm\lambda^{1/2}[(m_t^2-x_2),m_t^2,M^2]\lambda^{1/2}[(m_t^2-x_2),m_b^2,m_w^2]\}$$
$$-M^2,$$

$$x_2^-=m_t^2-(m_t-M)^2,\quad x_2^+=m_t^2-(m_b+m_w)^2. \tag{5}$$

Here $\lambda(x,y,z)\equiv(x-y-z)^2-4yz$. Setting $\alpha_s=0.253$, $m_c=1.5$ GeV, $m_b=4.9$ GeV, $m_t=176$ GeV [8], and $|\mathcal{M}_8(J/\psi)|^2=0.68\times10^{-3}$ GeV^2 [10], we get a branching ratio of

$$B(t\to W^+bJ/\psi)\approx1.46\times10^{-4}. \tag{6}$$

The dominant color-singlet prompt J/ψ production process is $t\to W^+bg^*$ with $g^*\to J/\psi gg$, and $g^*\to\chi_{cJ}g$ followed by $\chi_{cJ}\to J/\psi\gamma$, as shown in Fig. 2. We can estimate the partial widths following the method in Ref. [14]. The differential decay rate of $t\to W^+bg^*$ is similar to Eq. (4), and can be easily obtained or found in Ref. [15]. With the definition

$$\Gamma(g^*\to AX)=\pi\mu^3P(g^*\to AX), \tag{7}$$

the decay distributions $P(g^*\to\chi_{cJ}g)$ and $P(g^*\to J/\psi gg)$ for the gluon of virtuality μ can be found in Ref. [4] and Ref. [16]:

$$\mu^2P(g^*\to\chi_{c0}g)=\frac{r(1-3r)^2}{1-r}C_p, \tag{8}$$

$$\mu^2P(g^*\to\chi_{c1}g)=\frac{6r(1+r)}{1-r}C_p, \tag{9}$$

$$\mu^2P(g^*\to\chi_{c2}g)=\frac{2r(1+3r+6r^2)}{1-r}C_p, \tag{10}$$

$$\mu^2 P(g^* \to J/\psi gg) = C_s r \int_{2\sqrt{r}}^{1+r} dx_{J/\psi} \int_{x_-}^{x_+} dx_1 f(x_{J/\psi}, x_1; r), \tag{11}$$

where $r \equiv M/\mu$, M is the mass of the relevant charmonium states, and

$$C_p = \frac{8\alpha_s^2}{9\pi} \frac{|R_p'(0)|^2}{M^5}, \quad C_s = \frac{5\alpha_s^3}{27\pi^2} \frac{|R_s(0)|^2}{M^3}. \tag{12}$$

The function $f(x_{J/\psi}, x_1; r)$ in Eq. (11) is of the form

$$\begin{aligned} f(x_{J/\psi}, x_1; r) = & \frac{(2+x_2)x_2}{(2-x_{J/\psi})^2(1-x_1-r)^2} \\ & + \frac{(2+x_1)x_1}{(2-x_{J/\psi})^2(1-x_2-r)^2} \\ & + \frac{(x_{J/\psi}-r)^2-1}{(1-x_2-r)^2(1-x_1-r)^2} \\ & + \frac{1}{(2-x_{J/\psi})^2}\left(\frac{6(1+r-x_{J/\psi})^2}{(1-x_2-r)^2(1-x_1-r)^2} \right. \\ & \left. + \frac{2(1-x_{J/\psi})(1-r)}{(1-x_2-r)(1-x_1-r)r} + \frac{1}{r} \right), \end{aligned} \tag{13}$$

where $x_i \equiv 2E_i/\mu$ with $i = J/\psi$, g_1, g_2 are the energy fractions carried by the J/ψ and two gluons in the g^* rest frame, and then $x_2 = 2 - x_1 - x_{J/\psi}$. The limits of the x_1 integration in Eq. (11) are

$$x_\pm = \tfrac{1}{2}(2 - x_{J/\psi} \pm \sqrt{x_{J/\psi}^2 - 4r}). \tag{14}$$

We can evaluate the total decay rates of top quark to various color-singlet charmonium states A via

$$\Gamma(t \to W^+ bg^*; g^* \to AX) = \int_{M^2}^{m_t^2/4} d\mu^2 \Gamma(t \to W^+ bg^*(\mu^2)) P(g^* \to AX). \tag{15}$$

In the numerical estimation, we take $\alpha_s = 0.253$, $m_c = 1.5$ GeV, $M = 2m_c$, $|R_s(0)|^2 = 0.999$ GeV^3, and $|R_p'(0)|^2 = 0.125$ GeV^5 [17], and get

$$B(t \to W^+ b \chi_{c0} g) B(\chi_{c0} \to J/\psi\gamma) = 2.49 \times 10^{-9}, \tag{16}$$

$$B(t \to W^+ b \chi_{c1} g) B(\chi_{c1} \to J/\psi\gamma) = 5.35 \times 10^{-6}, \tag{17}$$

$$B(t \to W^+ b \chi_{c2} g) B(\chi_{c2} \to J/\psi\gamma) = 1.88 \times 10^{-6}, \tag{18}$$

$$B(t \to W^+ b J/\psi gg) = 1.39 \times 10^{-6}. \tag{19}$$

The χ_{cJ} production rates depend on the infrared cutoff. Here we take the cutoff $\mu_{\min}^2 = 2M^2$, which is the same as that in the fragmentation analysis [18]. Adding the branching ratios together, we obtain the total color-singlet prompt J/ψ production rate to be 8.6×10^{-6}, which is about a factor of 20 smaller than that via the color-octet production mechanism.

In conclusion, we have considered the color-octet charmonium production in top quark decays, and found the branching ratio of this dominant process, $t \to W^+ bJ/\psi$, to be 1.46×10^{-4}, which is over an order of magnitude larger than that of direct color-singlet J/ψ production processes. Such a large difference makes the process of J/ψ production in top quark decays another important channel to identify color-octet qurkonium signals whenever there are enough top quark events at the Fermilab Tevatron, CERN Large Hadron Collider (LHC), or Next Linear Collider (NLC) in the future.

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