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BRIEF REPORTS

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Estimates of $\chi_{cJ}(2P)$ production rates in B and $\Upsilon(1S)$ decays

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Assuming the hypothetical charmonium $\chi_{c,J}(2P)$ states solve the ψ' puzzle at the Fermilab Tevatron, we estimate the production rates of these new states in B and Υ decays, using the Bodwin-Braaten-Lepage factorization approach. We find that $B(B \to \chi_{c,J=1(2)}(2P) + X) \approx 0.3$–$0.5\,\%$ and $B(\Upsilon(1S) \to \chi_{c,J=1(2)}(2P) + X) \approx 0.8\ (1.2) \times 10^{-4}$ or less. Searches for inclusive decays of B and Υ into $\chi(2P)$ states are worthwhile to do in the current and future B factories.

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It is commonly believed that the production of a heavy quarkonium state in high energy processes can be adequately described by perturbative QCD (PQCD) [1]. However, recent observations of inclusive J/ψ and ψ' productions at high p_T at the Fermilab Tevatron provide the PQCD practitioners with a serious challenge to cope with the excess of data over theoretical estimates [2]. For J/ψ production, the lowest order subprocess comes from gluon-gluon fusion, which is smaller than the data by more than an order of magnitude. If one includes the gluon fragmentation into J/ψ (which is next-to-leading order in α_s), one gets higher theoretical estimates that still underestimate the experimental yield by a factor of 3–5. For ψ' production, the situation is even worse. Even with gluon fragmentation included, the theoretical production rate falls below the data by a factor of ~ 30 or so.

In order to resolve this puzzle, there have been basically two scenarios suggested up to now: (i) the existence of new charmonium states above the $D\bar{D}$ threshold, which can decay into J/ψ and ψ' with appreciable branching ratios [3–5], and (ii) the importance of gluon fragmentation into a pointlike color-octet S-wave $c\bar{c}$ state, and its subsequent evolution into ψ' [6]. Both scenarios are quite intriguing in the sense that they call for new elements of physics within the standard model—*new spectroscopy* or a *new production mechanism* for charmonium states. It would be useful to explore and test these possibilities in places other than $p\bar{p}$ colliders such as the Fermilab Tevatron.

In this Brief Report, we consider the first scenario, and try to see if one can find these hypothetical charmonium states in B and $\Upsilon(1S)$ decays. More specifically, we consider $\chi_{cJ}(2P)$ states, since these have been suggested as a possible solution to the ψ' puzzle at the Fermilab Tevatron [5]. We estimate the branching ratios of $B \to \chi_{cJ}(2P) + X$ and $\Upsilon(1S) \to \chi_{cJ}(2P) + X$ using the factorization developed by Bodwin, Braaten, and Lepage [7]. Discussions of the results are given at the end.

Although no charmonium states have been discovered above the $D\bar{D}$ threshold, there are predictions for the masses and decay widths of such resonances in potential models and flux tube models for heavy quarkonia [8]. Although the detailed properties depend on the resonance masses and other model parameters, it is possible to have $\chi_{cJ}(2P)$ states with total widths being relatively small (1–5 MeV) and the branching ratio into $\psi' + \gamma$ being $\sim$ (1–10)%. In order to be as model independent as possible in this work, we make a minimal assumption that there exist $\chi_{cJ}(2P)$ and $h_c(2P)$ states above the $D\bar{D}$ threshold with masses around ~ 3.9 GeV, ignoring the mass splittings among different $^{2S+1}P_J$ states. Instead of using the model predictions to the total decay rates and branching ratios into $\psi' + \gamma$, we adopt those values which can explain the ψ' anomaly at the Collider Detector at Fermilab (CDF), and explore the possibility that such states can be found in other processes such as decays of the B meson and $\Upsilon(1S)$ state.

The effective Hamiltonian for $b \to c\bar{c}q$ (with $q = d, s$) is written as [7]

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$$H_{\rm eff} = \frac{G_F}{\sqrt{2}}\, V_{cb}V_{cq}^* \left[\frac{2C_+ - C_-}{3}\; \bar{c}\gamma_\mu(1-\gamma_5)c\; \bar{q}\gamma^\mu(1-\gamma_5)b \;+ (C_+ + C_-)\; \bar{c}\gamma_\mu(1-\gamma_5)T^a c\; \bar{q}\gamma^\mu(1-\gamma_5)T^a b\right], \qquad (1)$$

where the $C_\pm$'s are the Wilson coefficients at the scale $\mu \approx m_b$. We have neglected penguin operators, since their Wilson coefficients are small and thus they are irrelevant to our case. To leading order in $\alpha_s(m_b)$ and to all orders in $\alpha_s(m_b)\ \ln(M_W/m_b)$, the above Wilson coefficients are

$$C_+(m_b) \approx 0.87, \qquad C_-(m_b) \approx 1.34. \qquad (2)$$

According to the factorization theorem for charmonium production in B decays by Bodwin *et al.*, one has

$$\Gamma(b \to h_c + X) = H_1 \hat{\Gamma}_1(b \to c\bar{c}(^1P_1) + X;\mu) + 3H_8'(\mu)\ \hat{\Gamma}_8(b \to c\bar{c}(^1S_0) + X), \qquad (3)$$

$$\Gamma(b \to \chi_{cJ} + X) = H_1 \hat{\Gamma}_1(b \to c\bar{c}(^3P_1) + X;\mu) + (2J+1)\ H_8'(\mu)\ \hat{\Gamma}_8(b \to c\bar{c}(^3S_1) + X), \qquad (4)$$

where $\hat{\Gamma}_{1,8}$ are rates for hard subprocesses of a b quark decaying into a $c\bar{c}$ pair with suitable angular momentum and vanishing relative momentum in the color-singlet and the color-octet states, respectively. H_1 and H_8' contain nonperturbative effects, and are proportional to the probablities that a $c\bar{c}$ in color-singlet P-wave and a $c\bar{c}$ in color-octet S-wave states fragment into color-singlet P-wave $c\bar{c}$ bound states such as physical $\chi_{cJ}(P)$ and $h_c(P)$ states. The parameter H_1 is related to the nonrelativistic quarkonium wave function as

$$H_1(nP) \approx \left(\frac{9}{2\pi}\right) \frac{|R_{nP}'(0)|^2}{m_c^4}. \qquad (5)$$

Note that the dependence on the radial quantum numbers n enters only through the nonperturbative parameters H_1 and H_8'.

From the decays of $\chi_{c1,2}(1P)$ into light hadrons, one gets

$$H_1(1P) \approx 15 \text{ MeV}. \qquad (6)$$

In Ref. [5], it was assumed that

$$H_1(2P) = H_1(1P) = 15 \text{ MeV}. \qquad (7)$$

However, one has information on these quantities from potential model calulations. Recently, Eichten and Quigg tabulated the predictions of various potential models for the $H_1(2P)/H_1(1P)$, which can be summarized as

$$H_1(2P) = (0.97, 1.05, 1.36, 1.42) \times H_1(1P) \qquad (8)$$

for the logarithmic, power law, Buchmuller-Tye, and Cornell potentials, respectively [9]. The actual value is important only for the case of $B \to \chi_{c,J=1}(2P) + X$. We present the results for $H_1(2P) = 15$ MeV and 20 MeV below.

The other nonperturbative parameter $H_8'(m_b)$ was roughly estimated to be ≈ 3 MeV in Ref. [7], assuming m_b is very large. This value was also used in Ref. [5] in order to explain the surplus of ψ' production at the CDF through gluon fragmentation into $\chi_{cJ}(2P)$'s with their subsequent "decays into $\psi' + \gamma$. However, the new measurement of $B(B \to \chi_{c2}(1P) + X) = (0.25 \pm 0.11)\%$ yield $H_8'(m_b) \approx (1.7 \pm 0.7)$ MeV for $m_b = 5.3$ GeV [6]. Since theoretical calculations are of leading order in $O(\alpha_s)$, either of these two values would be fine for our purpose. Therefore, we shall use $H_8'(m_b)(1P) = H_8'(m_b)(2P) \approx 3$ MeV and 2.0 MeV for estimating the production rates of $\chi_{c1,2}(2P)$ in B and $\Upsilon(1S)$ decays. One has to keep in mind that the approximations $H_1(2P) = 15$ MeV or 20 MeV and $H_8'(2P) = H_8'(1P)$ induce some uncertainties in the final results, although they happen to give a reasonable description of ψ' production at the CDF [5].

After all, using $m_c \approx M(J/\psi)/2$ GeV we get the branching ratios as shown in Table I for $H_1(2P) = 15$ MeV and $H_8'(M_b) = 3$ MeV and 2 MeV, respectively. [The case $H_1(2P) = 20$ MeV is shown in the parentheses for $B \to \chi_{c,1}(2P) + X$.] Note that scenario (i) predicts that hypothetical $\chi_{cJ}(2P)$ states should be observed in the near future in the decay chain $B \to \chi_{c1,2}(2P) + X$ followed by $\chi_{c1,2} \to \psi' + \gamma$. If one assumes that the branching ratio of the latter decay is $\sim 10\%$ in order to solve the ψ' anomaly at the CDF, one would have ~ 36 (47)

TABLE I. Branching ratios for $B \to \chi_{cJ}(2P) + X$ and $h_c(2P) + X$ for $H_1(2P) = 15$ (20) MeV and two values of $H_8'(M_b)$ (≈ 3 MeV and 2 MeV, respectively).

Decay mode	$H_8'(M_b) = 3$ MeV	$H_8'(M_b) = 2$ MeV
$B \to \chi_{c0}(2P) + X$	0.09%	0.06%
$B \to \chi_{c1}(2P) + X$	0.36%(0.39%)	0.27%
$B \to \chi_{c2}(2P) + X$	0.47%	0.31%
$B \to h_c(2P) + X$	0.50%	0.33%

TABLE II. Branching ratios for $\Upsilon(1S) \to \chi_{cJ}(2P) + X$ for $H_1(2P) = 15$ (20) MeV and two values of $H_8'(M_b)$ (≈ 3.0 MeV and 2.0 MeV, respectively). (−) means a negative branching ratio which is nonphysical.

Decay modes	$H_8'(M_b) = 3$ MeV	$H_8'(M_b) = 2$ MeV
$\Upsilon(1S) \to \chi_{c0}(2P) + X$	$1.8\ (0.79) \times 10^{-5}$	$1.9(-) \times 10^{-6}$
$\Upsilon(1S) \to \chi_{c1}(2P) + X$	$8\ (5.8) \times 10^{-5}$	$3.2\ (1.0) \times 10^{-5}$
$\Upsilon(1S) \to \chi_{c2}(2P) + X$	$1.2\ (0.8) \times 10^{-4}$	$4.2\ (0.25) \times 10^{-5}$

events among 10^5 B decays, $B \to \chi_{c1(2)}(2P) + X$ followed by $\chi_{c1(2)} \to \psi' + \gamma$. These chains, if existent, will contribute to $B \to \psi' + X$ by an amount of (0.03–0.05)% in the branching ratio, which is about 10% of the observed rate, $B(B \to \psi' + X) = (0.34 \pm 0.04 \pm 0.03)\%$. So the first scenario for the ψ' puzzle at the CDF by Roy and Sridhar [5] can be easily tested in current and future CLEO experiments.

The factorization theorem developed by Bodwin *et al.* has been applied to P-wave charmonium production in Υ decays by Trottier [10]. In anology to Eqs. (3) and (4), one has

$$\Gamma(\Upsilon(1S) \to \chi_{cJ}(nP) + X) = H_1 \hat{\Gamma}_1(\Upsilon(1S) \to c\bar{c}(^3P_J) + X; \mu) + (2J+1)\, H_8'(\mu)\, \hat{\Gamma}_8(\Upsilon(1S) \to c\bar{c}(^3S_1) + X). \quad (9)$$

Here, $\hat{\Gamma}_{1,8}$ are the production rates of a $c\bar{c}$ pair in color-singlet P-wave and color-octet S-wave states in $\Upsilon(1S)$ decays, and H_1 and $H_8'(\mu)$ are the same as in the case of B meson decays. The factorization scale μ is $= O(m_\Upsilon)$ in order to avoid large logarithms in $\hat{\Gamma}_1(\mu)$. The rates for the hard subprocesses, $\hat{\Gamma}_{1,8}$, have been calculated in Ref. [10] to leading order in α_s:

$$\hat{\Gamma}_1 = \frac{20\alpha_s^5}{3^7\pi^3} \frac{G_1^\Upsilon}{m_\chi} \mathcal{F}_{1J}(\mu), \quad (10)$$

$$\hat{\Gamma}_8 = \frac{20\alpha_s^4}{3^7\pi^3} \frac{G_1^\Upsilon}{m_\chi} \mathcal{F}_8. \quad (11)$$

The parameter $G_1^\Upsilon \approx 108$ MeV is related to $\Upsilon(1S) \to e^+e^-$, and we use $\alpha_s(m_b) \approx 0.179$. For $\mu = m_\Upsilon$, the functions $\mathcal{F}_{1J}$'s and $\mathcal{F}_8$ are given as functions of m_χ/m_Υ in Ref. [10]. For $m_\chi = 3.9$ GeV, one has

$$F_{1,J=0} \approx -70 \times 1, F_{1,J=1} \approx -50 \times 3, \quad (12)$$

$$F_{1,J=2} \approx -55 \times 5, F_8 \approx 100. \quad (13)$$

For this decay, if too small a $H_8'(M_b)$ or too large a $H_1(2P)$ is chosen, one may get negative decay rates for $\chi_{c,J}(2P)$ production, because of cancellation between the color-singlet and the color-octet contributions in Eq. (9). This is clearly nonphysical, and may be due to the higher order terms in v^2 and α_s that have been neglected in Ref. [10]. So we take $H_8' = 3.0$ MeV and 2.0 MeV. (Note that $H_8' = 3.0$ MeV was assumed in Ref. [5] to solve the ψ' anomaly.) Using these numbers in Eq. (9), one obtains the results shown in Table II. Since $B(\Upsilon(1S) \to \chi_{cJ}(2P) + X) \sim$ (a few) $\times 10^{-5}$, one has to acculmulate more than 10^6 $\Upsilon(1S)$ decays in order to see the hypothetical $\chi_{cJ}(2P)$ states which may solve the ψ' anomaly at the CDF.

In this Brief Report, we gave estimates for the production rates for the hypothetical $\chi_{cJ}(2P)$ states in the B and Υ decays, assuming they are a solution to the ψ' puzzle at the CDF. Under the same assumptions adopted in Ref. [5], we find that the branching ratios for $B(B \to \chi_{c,J=1,2}(2P) + X) \approx$ (0.3–0.5)%, which are well within reach of the CLEO experiments. A search for $\chi_{cJ}(2P)$ states in $\Upsilon(1S)$ decays requires more than 10^6 $\Upsilon(1S)$ decays. Also, a search for these hypothetical states in other experiments such as $p\bar{p} \to \chi_{cJ}(2P) \to \psi'\gamma$ in the Fermi Lab E760 experiment could be equally important to better understand those problems discussed in this work.

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