Title
Gluon fragmentation to ^3D_J quarkonium and test of color-octet production mechanism

Authors
Chao, Kuang-Ta
Qiao, Cong-Feng
Yuan, Feng

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Crucial test for the color-octet production mechanism in Z^0 decays

Cong-Feng Qiao, Feng Yuan, and Kuang-Ta Chao
Department of Physics, Peking University, Beijing 100871, People's Republic of China
and China Center of Advanced Science and Technology (World Laboratory), Beijing 100080, People's Republic of China

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The direct production rates of D-wave charmonia in the decays of Z^0 are evaluated. The color-octet production processes $Z^0 \to {}^3D_J(c\bar{c})q\bar{q}$ are shown to have distinctively large branching ratios as compared with other D-wave charmonium production mechanisms under a proper assumption. This may suggest a crucial channel to test the color-octet mechanism as well as to observe the D-wave charmonium states in Z^0 decays. In addition, a signal for the ${}^3D_J$ charmonium states with a large transverse momentum at the Fermilab Tevatron should be observed. [S0556-2821(97)02507-1]

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The systematic study of the heavy quark bound systems has played a very important role in obtaining information not only on the properties of heavy quarks themselves but also on quantum chromodynamics (QCD). Recent progress in the this area was stimulated by the experimental results of the Collider Detector at Fermilab (CDF) Collaboration at the Tevatron. In the 1992–1993 run, the CDF data [1] for the prompt production of ψ and ψ' at large transverse momentum were observed to be orders of magnitude stronger than the lowest order perturbative calculations based on the color-singlet model [2]. Furthermore, various parton (gluon and quark) fragmentation mechanisms have been suggested to resolve this surplus problem but the calculated rates are still too small [3]. These large discrepancies have called into question the simple color-singlet model description for quarkonium and stimulates one to seek new production mechanisms as well as new paradigms for treating heavy quark-antiquark bound systems that go beyond the color-singlet model.

To this end, a factorization formalism has recently been performed by Bodwin, Braaten, and Lepage [4] in the context of nonrelativistic quantum chromodynamics (NRQCD), which provides a new framework to calculate the inclusive production and decay rates of quarkonia. In this approach, the calculations are organized in powers of v, the average velocity of the heavy quark (antiquark) in the meson rest frame, and in α_s, the strong-coupling constant.

The breakdown of the color-singlet model stems from its overlook of the high Fock components contributions to quarkonium production cross sections. The lowest order color-octet contribution in the gluon fragmenting to $\psi(\psi')$ has been considered by Braaten and Fleming [5] to explain the $\psi(\psi')$ surplus problem discovered by CDF. Taking $\langle \mathcal{O}_8^{\psi}({}^3S_1)\rangle$ and $\langle \mathcal{O}_8^{\psi'}({}^3S_1)\rangle$ as input parameters, the CDF surplus problems for ψ and ψ' can be explained as the contributions of color-octet terms due to gluon fragmentation.

Even though the color-octet mechanism has gained some successes in describing the production and decays of heavy quark bound systems [4,6], it still has a long way to go before finally setting its position and role in heavy quarkonium physics. Therefore, the most urgent task, among others, is to confirm and identify the color-octet quarkonium signals.

While the first charmonium state, J/ψ was found over twenty years ago, D-wave states, given the limited experimental data, have received less attention. However, this situation may be changed in both experimental and theoretical investigations. Experimentally, there are hopes of observing charmonium D-wave states in addition to the $1^{--}\,\psi(3770)$, in a high-statistic exclusive charmonium production experiment [7] and $b\bar{b}$ D-wave states in Υ radiative decays [8].

Recently, there is some clue for the D-wave 2^{--} charmonium state in $E705$ 300 GeV $\pi^{\pm}$- and proton-Li interaction experiments [9]. In this experiment there is an abnormal phenomenon that in the $J/\psi\pi^+\pi^-$ mass spectrum, two peaks at $\psi(3686)$ and at 3.836 GeV (given to be the 2^{--} state) are observed and they have almost the same height. Obviously, this situation is difficult to explain based upon the color-singlet model. However, it might be explained with the NRQCD analysis. In NRQCD the Fock state expansion for ${}^3D_J$ states is

$$|{}^3D_J\rangle = O(1)|Q\bar{Q}({}^3D_J,\underline{1})\rangle + O(v)|Q\bar{Q}({}^3P_{J'},\underline{8})g\rangle + O(v^2)|Q\bar{Q}({}^3S_1,\underline{8}\text{ or }\underline{1})gg\rangle + \cdots. \quad (1)$$

In the quark fragmentation for D-wave charmonium production processes, all the three terms in Eq. (1) are of the same order in both α_s and v^2. However, in the gluon fragmentation processes, the S-wave color-octet $({}^3S_1,\underline{8})$ production is $O(1/\alpha_s^2)$ enhanced over the color-singlet $({}^3D_J,\underline{1})$ and $({}^3S_1,\underline{1})$ production in the short-distance perturbative sector because the color singlet $({}^3D_J,\underline{1})$ and $({}^3S_1,\underline{1})$ have to couple to at least three gluons. The P-wave color-octet process is forbidden by charge conjugation invarance. By this argument, it might be easy to understand the E705 experiment data as long as the nonperturbative matrix element $\langle \mathcal{O}_8^{{}^3D_2}({}^3S_1)\rangle$ is about the same order in v^2 as $\langle \mathcal{O}_8^{\psi'}({}^3S_1)\rangle$ in magnitude, which may be true in the sense of NRQCD velocity expansion of fermion operators.

Of course, at energies in fixed target experiments such as E705, the color-octet gluon fragmentation dominance may or may not be the case. Moreover, the strong signal of $J/\psi\pi^+\pi^-$ at 3.836 GeV observed by E705 is now ques-

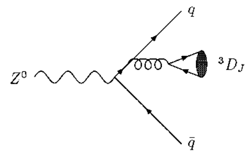

FIG. 1. One of the contributing Feynman diagrams of color-octet mechanism in $Z^0 \to {}^3D_J q\overline{q}$ processes.

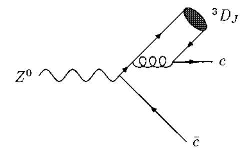

FIG. 2. One of the Feynman diagrams corresponding to quark fragmentation processes in Z^0 decays.

tioned by other experiments [10]. Nevertheless, if the E705 result is confirmed (even with a smaller rate, say, by a factor of 3 for the signal at 3.836 GeV), the color-octet gluon fragmentation will perhaps provide a quite unique explanation for the D-wave charmonium production. It does remind us that in the NRQCD approach the production rates of D-wave heavy quarkonium states can be as large as that of S-wave states as long as the color-octet gluon production mechanism dominantes. This scenario can be tested in many processes, for instance, in the Z^0 decays.

Recently, a study showed [11] that the leading order color-octet process in α_s, say $Z^0 \to \psi g$, has a relatively small branching ratio because of the large momentum transfer, and this is also the case for the D-wave charmonium production. The dominant color-octet processes for $Z^0 \to {}^3D_J q\overline{q}$ as well as $Z^0 \to \psi q\overline{q}$ begin at order α_s^2 as shown in Fig. 1. Here q represents u,d,s,c, or b quarks. From Ref. [11] we readily have

$$\Gamma(Z \to {}^3D_J q\overline{q}) = \Gamma(Z \to q\overline{q}) \frac{\alpha_s^2(2m_c)}{36} \frac{\langle \mathcal{O}_8^{^3D_J}(^3S_1)\rangle}{m_c^3} \times \left\{ 5(1-\xi^2) - 2\xi\ln\xi + \left[2\mathrm{Li}_2\left(\frac{\xi}{1+\xi}\right) - 2\mathrm{Li}_2\left(\frac{1}{1+\xi}\right) - 2\ln(1+\xi)\ln\xi + 3\ln\xi + \ln^2\xi \right](1+\xi)^2 \right\} \quad (2)$$

in the limit $m_q = 0$, where $\mathrm{Li}_2(x) = -\int_0^x dt \ln(1-t)/t$ is the Spence function. The calculation with physical masses, say, e.g., $m_b = 5$ GeV, has also been performed by us, which does not show much difference from the case of $m_q = 0$.

From Eq. (2) (with slight modification due to nonzero m_q), we can get the branching ratios of $Z^0 \to {}^3D_J q\overline{q}$. In the numerical calculation, we take [12,13]

$$m_c = 1.5 \text{ GeV}, \quad M_{^3D_J} \approx 2m_c, \quad \alpha_s(2m_c) = 0.253 \quad (3)$$

and assume

$$\langle \mathcal{O}_8^{^3D_2}(^3S_1)\rangle \approx \langle \mathcal{O}_8^{\psi'}(^3S_1)\rangle = 4.6 \times 10^{-3} \text{GeV}^3. \quad (4)$$

Here, because in NRQCD $\langle \mathcal{O}_1^{^3D_J}(^3D_J)\rangle$ is of order v^7, the same as $\langle \mathcal{O}_8^{^3D_J}(^3S_1)\rangle$, and in the nonrelativistic expansion of the four-fermion production operators, $\langle \mathcal{O}_1^{^3D_J}(^3D_J)\rangle$ is v^4 suppressed relative to $\langle \mathcal{O}_1^{J/\psi}(^3S_1)\rangle$, which is also the conclusion of the potential model calculations, we may infer that $\langle \mathcal{O}_8^{^3D_J}(^3S_1)\rangle$ is of the same order as $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle$ or $\langle \mathcal{O}_8^{\psi'}(^3S_1)\rangle$. In view of this, although we know that the NRQCD velocity scaling rules says nothing about how different matrix elements of operators that projected onto different physical states should be scaled, the assumption of relation (4) may still be convincing to some extent. As an ansatz, in the following computation we tentatively take the relation of Eq. (4), where the value of $\langle \mathcal{O}_8^{\psi'}(^3S_1)\rangle$ was determined by fitting the CDF data for surplus production of ψ' at the Tevatron [13]. From approximate heavy-quark spin symmetry relations, we have

$$\langle \mathcal{O}_8^{^3D_1}(^3S_1)\rangle \approx \tfrac{3}{5}\langle \mathcal{O}_8^{^3D_2}(^3S_1)\rangle, \langle \mathcal{O}_8^{^3D_3}(^3S_1)\rangle \approx \tfrac{7}{5}\langle \mathcal{O}_8^{^3D_2}(^3S_1)\rangle. \quad (5)$$

Summing over all the quark flavors $(q = u,d,s,c,b)$ with their physical masses, we obtain the decay widths

$$\sum_q \Gamma(Z^0 \to {}^3D_1 q\overline{q}) \approx 0.7 \times 10^{-4} \text{ GeV},$$

$$\sum_q \Gamma(Z^0 \to {}^3D_2 q\overline{q}) \approx 1.2 \times 10^{-4} \text{ GeV},$$

$$\sum_q \Gamma(Z^0 \to {}^3D_3 q\overline{q}) \approx 1.7 \times 10^{-4} \text{ GeV}, \quad (6)$$

and the fraction ratios

$$\frac{\Gamma(Z^0 \to {}^3D_1 q\overline{q})}{\Gamma(Z^0 \to q\overline{q})} = 2.0 \times 10^{-4},$$

$$\frac{\Gamma(Z^0 \to {}^3D_2 q\overline{q})}{\Gamma(Z^0 \to q\overline{q})} = 3.4 \times 10^{-4},$$

$$\frac{\Gamma(Z^0 \to {}^3D_3 q\overline{q})}{\Gamma(Z^0 \to q\overline{q})} = 4.8 \times 10^{-4}. \quad (7)$$

The dominant color-singlet processes occur as shown in Fig. 2 and Fig. 3. Corresponding to the quark fragmentation in Fig. 2, the branching ratios of charmonium ^3D_J production in color-singlet processes are 2.3×10^{-6}, 3.6×10^{-6}, and 1.7×10^{-6} for $J = 1,2,3$, respectively, which are obtained from the universal fragmentation calculations [14]. There

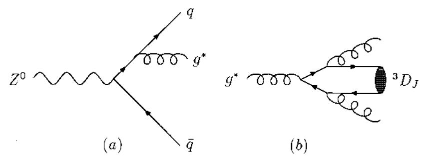

FIG. 3. Diagrams for ^3D_J production from gluon jet in color-singlet mechanisms. (a) virtual gluon production in Z^0 decays (b) ^3D_J production in gluon fragmentaion.

should also be color-octet processes through quark fragmentation as in Fig. 2. However, indirect evidence indicates that they are not donimant relative to the color-singlet processes [14].

The processes in Fig. 3 are more complicated. For in the most important kinematic region the virtual gluon is nearly on its mass shell, ^3D_J production in the gluon fragmentation color-singlet process may be separated to be $Z^0 \rightarrow q\overline{qg}^*$ with $g^* \rightarrow {}^3D_J gg$. We can estimate the partial width following the way in Ref. [15], and the differencial decay rate of $Z^0 \rightarrow q\overline{qg}^*$ may then be obtained. With the definition

$$\Gamma(g^* \rightarrow AX) = \pi \mu^3 P(g^* \rightarrow AX), \tag{8}$$

the calculation of decay distribution $P(g^* \rightarrow {}^3D_J gg)$ for the gluon of virtuality μ is very complicated and lengthy (the detailed calculation will be given elsewhere [16]), and in the nonrelativistic limit it is proportional to the second derivative of the radial wave function at the origin. As in the cases of P-wave charmonium production, $g^* \rightarrow {}^3D_J gg$ processes also have the infrared divergences involved, which are associated with the soft gluon in the final state. Strictly speaking, the divergences can be canceled in the framework of NRQCD, but here we simply deal with it following the way of Ref. [17] by imposing a lower cutoff Λ on the energy of the outgoing gluon in the quarkonium rest frame. As discussed in Ref. [17], the cutoff Λ can be set to be m_c to avoid large logarithms in the divergence terms.

The decay widths of Z^0 to color-singlet charmonium state ^3D_J by gluon fragmentation can be evaluated via

$$\Gamma(Z^0 \rightarrow q\overline{qg}^*; g^* \rightarrow {}^3D_J gg) = \int_{\mu^2_{\min}}^{M_Z^2} d\mu^2 \Gamma(Z^0 \rightarrow q\overline{qg}^*) P(g^* \rightarrow {}^3D_J gg), \tag{9}$$

where the cutoff $\Lambda = m_c$ is transformed into a lower limit on $\mu^2_{\min} = 12 m_c^2$.

In the numerical calculation, taking [12,18]

$$\alpha_s(2m_c) = 0.253, \quad m_c = 1.5 \text{ GeV},$$

$$|R''_D(0)|^2 = 0.015 \text{ GeV}^7, \tag{10}$$

and summing over all the flavors $q(q = u,d,s,c,b)$, we obtain

$$\frac{\Gamma(Z^0 \rightarrow q\overline{qg}^*; g^* \rightarrow {}^3D_1 X)}{\Gamma(Z^0 \rightarrow q\overline{q})} = 4.3 \times 10^{-7},$$

$$\frac{\Gamma(Z^0 \rightarrow q\overline{qg}^*; g^* \rightarrow {}^3D_2 X)}{\Gamma(Z^0 \rightarrow q\overline{q})} = 2.1 \times 10^{-6},$$

$$\frac{\Gamma(Z^0 \rightarrow q\overline{qg}^*; g^* \rightarrow {}^3D_3 X)}{\Gamma(Z^0 \rightarrow q\overline{q})} = 1.2 \times 10^{-6}. \tag{11}$$

Among the three triplet states of D-wave charmonium, $^3D_2$ is the most promising candidate to discover first. Its mass falls in the range of 3.810∼3.840 GeV in the potential model calculation [19], that is above the DD threshold but below the DD^* threshold. However, the parity conservation forbids it decaying into DD. It, therefore, is a narrow resonance. Its main decay modes are expected to be

$$^3D_2 \rightarrow J/\psi \pi\pi, \quad {}^3D_2 \rightarrow {}^3P_J \gamma (J = 1,2), \quad {}^3D_2 \rightarrow 3g. \tag{12}$$

We can estimate the hadronic transition rate of $^3D_2 \rightarrow J/\psi \pi^+ \pi^-$ from the Mark III data for $\psi(3770) \rightarrow J/\psi \pi^+ \pi^-$ [20] and the QCD multipole expansion theory [21,22]. The Mark III data give [20] $\Gamma(\psi(3770) \rightarrow J/\psi \pi^+ \pi^-) = (37 \pm 17 \pm 8)$ keV or $(55 \pm 23 \pm 11)$ keV (see also, Ref. [22]). Because the $S-D$ mixing angle for $\psi(3770)$ and $\psi(3686)$ is expected to be small (say, $-10°$, see Ref. [23] for the reasoning), the observed $\psi(3770) \rightarrow J/\psi \pi^+ \pi^-$ transition should dominantly come from the $^3D_1 \rightarrow J/\psi \pi^+ \pi^-$ transition, which is also compatible with the multipole expansion estimate [22]. Then using the relation [21]

$$d\Gamma({}^3D_2 \rightarrow {}^3S_1 2\pi) = d\Gamma({}^3D_1 \rightarrow {}^3S_1 2\pi)$$

and taking the average value of the $\Gamma(\psi(3770) \rightarrow J/\psi \pi^+ \pi^-)$ from the Mark III data, we may have

$$\Gamma({}^3D_2 \rightarrow J/\psi \pi^+ \pi^-) = \Gamma({}^3D_1 \rightarrow J/\psi \pi^+ \pi^-) \approx 46 \text{ keV}. \tag{13}$$

For the E1 transition $3D_2 \rightarrow {}^3P_J \gamma (J = 1,2)$, using the potential model with relativistic effects being considered [24], we find

$$\Gamma({}^3D_2 \rightarrow \chi_{c1} \gamma) = 250 \text{ keV},$$

$$\Gamma({}^3D_2 \rightarrow \chi_{c2} \gamma) = 60 \text{ keV}, \tag{14}$$

where the mass of $^3D_2$ is set to be 3.84 GeV. As for the $^3D_2 \rightarrow 3g$ annihilation decay, an estimate gives [25]

$$\Gamma({}^3D_2 \rightarrow 3g) = 12 \text{ keV}. \tag{15}$$

From Eqs. (13), (14), and (15), we find

$$\Gamma_{\text{tot}}({}^3D_2) \approx \Gamma({}^3D_2 \rightarrow J/\psi \pi\pi) + \Gamma({}^3D_2 \rightarrow \chi_{c1} \gamma) + \Gamma({}^3D_2 \rightarrow \chi_{c2} \gamma) + \Gamma({}^3D_2 \rightarrow 3g) \approx 390 \text{ keV}, \tag{16}$$

and

$$B({}^3D_2 \rightarrow J/\psi \pi^+ \pi^-) \approx 0.12. \tag{17}$$

Considering all the uncertainties this estimate is expected to hold within 50%. Compared (17) with $B(\psi'\rightarrow J/\psi\pi^+\pi^-)=0.324\pm0.026$, the branching ratio of $^3D_2\rightarrow J/\psi\pi^+\pi^-$ is only smaller by a factor of 3, and therefore the decay mode of $^3D_2\rightarrow J/\psi\pi^+\pi^-$ is observable, if the production rate of $^3D_2$ is of the same order as ψ'.

The other two states of the triplet, $^3D_1$ and $^3D_3$, are above the open channel thresholds and are not narrow, and therefore are difficult to detect. It might be interesting to note that the OPAL Collaboration at the CERN e^+e^- collider LEP has analyzed the $J/\psi\pi^+\pi^-$ spectrum in Z^0 decays [26], and there seems to be some events above the background around 3.77 GeV. Whether these events are associated with the D-wave 1^{--} charmonium state $\psi(3770)$ might remain interesting.

In conclusion, based upon the assumption of Eq. (4), from the calculations and discussions above one can clearly see that the branching ratios of gluon fragmenting to color-octet ^3D_J states are two to three orders larger than the dominant color-singlet processes. This large divergences are much helpful in distinguishing the two production mechanisms in experiment. On the other hand, from Eq. (4) the production rates of ψ' and $^3D_2(c\overline{c})$ in the color-octet mechanism are of the same amount of magnitude (within an error about v^2), the 2^{--} charmonium production in Z^0 decay may provide a crucial channel to test color-octet production mechanism at LEP with the present luminosity.

Finally, we would like to point out that if the assumption of Eq. (4) has a large error for D-wave matrix elements, more 10 times than it really is, the above conclusion may breakdown. However it definitely provides a possibility to find the charmonium D-wave states and to confirm the color-octet production mechanism in Z^0 decays. At the Tevatron, as in the case of J/ψ and ψ' production at large transverse momentum, the ^3D_J production will also be dominanted by the color-octet gluon fragmentation. Even with a suppression of ten times or more relative to the assumption of Eq. (4) for charmonium D-wave color-octet matrix elements, the D-wave states, especially the 2^{--}, are still observable with the present luminosity and the different production mechanisms can be distinguished from by measureing the energy distribution of the produced bound state. This will also present as a crucial test of the color-octet mechanism. Detailed analysis as involved with the gluon fragmentation color-singlet processes will be given elsewhere.

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