Estimating the Branching Ratio for the Charmonium: Two gluon decay

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Introduction

The production of heavy quarkonia received a lot of attention from both theory and experiment in recent years.The production of the J/Ψ charmonium bound state is currently under active study. A series of charmonium-like states called collectively XYZ states, have been observed by several major experimental collaborations such as Babar, BESIII, LHCb, CLEO-c, Belle,BES,CLEO and E835. New experimental measurements,mainly coming from Belle,BES,CLEO and E835 have improved existing data on inclusive and electromagnetic and several exclusive decay channels as well as on several electromagnetic and hadronic transition amplitudes.The main processes for the decay of charmonium states are electromagnetic annihilations,radiative transitions and hadronic annihilations and transitions. Among hadronic decays, we can consider annihilations and transitions. The first type of decays occurs when the $c\bar{c}$ pair annihilates into two, or more,gluons or light quarks. The hadronic transitions occur from one charmonium state to another one, mainly with the emission of a pion pair or of an η meson.They may be understood as two-step processes in which gluons are first emitted from heavy quarks and then recombine into light hadrons. The main dynamical mechanism of heavy-quarkonium decay into light particles is quark-antiquark annihilation. Since this happens at a scale $2m_Q$ (m_Q is the heavy quark mass), which is perturbative, the heavy quarks annihilate into the minimal number of gluons allowed by color conservation and charge conjugation. The gluons subsequently create light quark-antiquark pairs that form the final state hadrons. Decays of quarkonia states into gluons are extremely useful for the production and identification of resonances as well as the leptonic decay rates of quarkonia. They can also assist to recognize conventional mesons and multiquark structures. The even states in charge conjugation of quarkonium with $J \neq 1$ can annihilate into two gluons, much in the same way as they decay into two photons. The charmonium states ${}^1S_0$, ${}^3P_0$, ${}^3P_2$ and ${}^1D_2$ can decay into two gluons, which account for a substantial portion of the hadronic decays for states below $c\bar{c}$ threshold. The two gluon decay widths are given by [2], [3].

$$\Gamma(n\ {}^1S_0 \to 2g) = \frac{2\alpha_s^2}{3m_c^2}|R_{nS}(0)|^2\left(1+\frac{4.8\alpha_s}{\pi}\right) \tag{1}$$

$$\Gamma(n\ {}^3P_0 \to 2g) = \frac{6\alpha_s^2}{m_c^4}|R'_{nP}(0)|^2\left(1+\frac{9.5\alpha_s}{\pi}\right) \tag{2}$$

$$\Gamma(n\ {}^3P_2 \to 2g) = \frac{8\alpha_s^2}{5m_c^4}|R'_{nP}(0)|^2\left(1-\frac{2.2\alpha_s}{\pi}\right) \tag{3}$$

$$\Gamma(n\ {}^1D_2 \to 2g) = \frac{2\alpha_s^2}{3\pi m_c^6}|R''_{nD}(0)|^2 \tag{4}$$

It is natural that in the non-relativistic potential model of charmonium, the ratio of the two-photon and two-gluon widths of the charmonium decays does not depend on the wave function and slowly grows with increase of the charmonium mass because of the proportionality to $\frac{1}{\alpha_s^2}$. The mass of $c\bar{c}$ pair is large and the annihilations of $c\bar{c}$ into gluons are perturbative, so the two-gluon decay mode is dominant in the charmonium. The two gluon decay widths are sensitive to the behavior of the $q\bar{q}$ wave function and its derivatives near the origin. The χ_{cJ} states radiatively decay down to J/Ψ with the branching ratios 0.7%,, 27% and 14% for J=1,2 and 3 respectively. Estimates for their masses yield $M(\chi_{c0}(2P))$ = 3916 MeV, $M(\chi_{c1}(2P))$ = 3872 MeV and

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$M(\chi_{c2}(2P)) = 3929$ MeV.These mass values kinematically allow the S-wave transitions $\chi_{c0}(2P) \to DD$ and $\chi_{c1}(2P) \to D^*D$ to occur. We therefore expect the J = 0 and J = 1 excited χ_{cJ}s to be broad and to have negligible branching fractions to lower $c\bar{c}$ bound states. However, angular momentum and parity considerations require the analogous decays $\chi_{c2}(2P) \to DD$ and $\chi_{c2}(2P) \to D^*D$ for the J = 2 state to proceed via L = 2 partial waves. Although we cannot readily compute by how much these D-wave decays will be suppressed, it is possible that the branching fractions for $\chi_{c2}(2P)$ transitions to charmonium states below DD threshold could be significant.

Results and Discussions

We have also calculated the decay of two gluons into light hadrons and have made prediction for the branching ratio of the decay $\chi_{c2} \to$ 2g in a reliable way, by taking the experimental input to our theoretical model. The well established states confirm this. [6].

$$\frac{\Gamma(\chi_{c0}(1P) \to 2\gamma)}{\Gamma(\chi_{c0}(1P) \to 2g)} = \frac{BR(\chi_{c0}(1P) \to 2\gamma)}{1 - BR(\chi_{c0}(1P) \to \gamma J/\psi(1S))} \approx 2.26 \times 10^{-4}$$

$$\frac{\Gamma(\chi_{c2}(1P) \to 2\gamma)}{\Gamma(\chi_{c2}(1P) \to 2g)} = \frac{BR(\chi_{c2}(1P) \to 2\gamma)}{1 - BR(\chi_{c2}(1P) \to \gamma J/\psi(1S))} \approx 3.39 \times 10^{-4}$$

where $BR(\chi_{c0}(1P) \to \gamma J/\psi(1S)) = (1.27 \pm 0.06)\%$ and $BR(\chi_{c2}(1P) \to \gamma J/\psi(1S) = (19.2 \pm 0.7)\%$ are the PDG values [56]. In a conventional way the ratio of the two photon to two gluon widths of the charmonium decays is to be the branching ratio of $\chi_{c2} \to$ 2g and it is around 10^{-4}. The two gluon decay of $\chi_{c2}(2P)$ is via $D\bar{D}$ channel. The branching ratio calculated in our model is $BR(\chi_{c2}(2P) \to 2g) BR(\chi_{c2}(2P) \to D\bar{D}) = 3.32 \times 10^{-4}$. The hadron channels of the two-gluon decays of $\chi_{c2}(2P)$ could be the same as in the $\chi_{c2}(1P)$ case, that is, there are a few tens of such channels. It is known that the difference in the radial wave functions of $\chi_{c2}(1P)$ and $\chi_{c2}(2P)$ does not show a significant difference in $\Gamma(\chi_{c2}(1P) \to 2\gamma)$ and $\Gamma(\chi_{c2}(2P) \to 2\gamma)$. An identical conclusion may be made for $\Gamma(\chi_{c2}(1P) \to 2g)$ and $\Gamma(\chi_{c2}(2P) \to 2g)$, which implies the following condition.

$$\Gamma(\chi_{c2}(2P) \to 2g) \approx \Gamma(\chi_{c2}(1P) \to 2g) = \Gamma(\chi_{c2}(1P))(1 - BR(\chi_{c2}(1P) \to \gamma J/\psi(1S)).$$

In our model $\Gamma(\chi_{c2}(2P) \to 2g)$= 2.15 MeV. Taking into account $\Gamma(\chi_{c2}(2P)) \approx 24$ MeV [56] we then obtain the $BR(\chi_{c2}(2P) \to 2g) \approx 8.9\%$. The corresponding PDG value is $BR(\chi_{c2}(2P) \to 2g) \geq (2 \pm 0.4)\%$.

Two-Gluon Decay widths (MeV)

State	Present Γ Work	Exp	[1]	[5]
$\eta_c(1S)$	27.61	28.6 ± 2.2	22.048	15.70
$\eta_c(2S)$	7.92	14 ± 7	8.496	8.10
$\eta_c(3S)$	5.67		5.696	
$\chi_{c0}(1P)$	9.67	10.3 ± 0.6	6.114	4.68
$\chi_{c0}(2P)$	3.67		3.775	
$\chi_{c2}(1P)$	2.15	1.97 ± 0.11	0.633	1.72
$\chi_{c2}(2P)$	2.59		0.401	
1^1D_2	0.068		0.014	
2^1D_2	0.061		0.012	

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