On the nature of $\chi_{c2}(2P)$: two-gluon decay

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Abstract: We expect that $BR(\chi_{c2}(2P)\to\text{gluongluon})\gtrsim 2\%$ if the Particle Data Group as well as the BaBar and Belle collaborations have correctly identified the state. In reality, this branching ratio corresponds to the one for $\chi_{c2}(2P)$ decaying into light hadrons. We also discuss the detection possibilities of these decays.

Keywords: charmonium, branching ratio, two-gluon decay mode

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1 Introduction

More and more XYZ states have been observed in experiments, and their interpretation is still challenging to the community. Some of these states, however, may just be quarkonium states.

In 2006, the Belle collaboration reported a resonance with 5.3σ statistical significance of the signal via the $\gamma\gamma\to D\bar{D}$ process [1]. The properties of the mass, angular distributions, and $\Gamma_{\gamma\gamma}\Gamma_{D\bar{D}}/\Gamma$ (see also Eq. (6) below) are all consistent with the 2^3P_2 charmonium state, now identified by the Particle Data Group (PDG) as $\chi_{c2}(2P)$ [2]. Later, the BaBar collaboration [3] confirmed this observation using data samples of comparable magnitude with those of Belle. Its mass and width are $M=3927.2\pm2.6$ MeV and $\Gamma=24\pm6$ MeV, respectively [2]. To date, only the quantity $\Gamma_{\gamma\gamma}\Gamma_{D\bar{D}}/\Gamma$ has been determined, except for the constrained upper limit for the product of the branching ratio for $\gamma\gamma$ and some selected hadronic states [4–6]. Little is known beyond them, especially for the branching ratio of hadronic decays. In this article, we will predict the branching ratio of the decay $\chi_{c2}\to 2g$ (g denoting gluon) in a reliable way, by combining the observation of the known experimental facts and the successful application of the charmonium model [7]. In practice, that branching ratio corresponds to summing over those for light hadronic decay.

2 Discussion on branching ratios

It is natural that in the nonrelativistic 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 increasing charmonium mass, because of the proportionality to $1/\alpha_s^2$. See, for example, Ref. [7]. The well established states [2] confirm this consideration:

$$BR(\eta_c(1S)\to 2\gamma) = \frac{\Gamma(\eta_c(1S)\to 2\gamma)}{\Gamma(\eta_c(1S))} = \frac{\Gamma(\eta_c(1S)\to 2\gamma)}{\Gamma(\eta_c(1S)\to 2g)}\approx 1.59\times10^{-4}, \quad (1)$$

$$\frac{\Gamma(\chi_{c0}(1P)\to 2\gamma)}{\Gamma(\chi_{c0}(1P)\to 2g)} = \frac{\Gamma(\chi_{c0}(1P)\to 2\gamma)}{\Gamma(\chi_{c0}(1P))-\Gamma(\chi_{c0}(1P)\to\gamma J/\psi(1S))} = \frac{BR(\chi_{c0}(1P)\to 2\gamma)}{1-BR(\chi_{c0}(1P)\to\gamma J/\psi(1S))}\approx 2.26\times10^{-4}, \quad (2)$$

$$\frac{\Gamma(\chi_{c2}(1P)\to 2\gamma)}{\Gamma(\chi_{c2}(1P)\to 2g)} = \frac{\Gamma(\chi_{c2}(1P)\to 2\gamma)}{\Gamma(\chi_{c2}(1P))-\Gamma(\chi_{c2}(1P)\to\gamma J/\psi(1S))} = \frac{BR(\chi_{c2}(1P)\to 2\gamma)}{1-BR(\chi_{c2}(1P)\to\gamma J/\psi(1S))}\approx 3.39\times10^{-4}, \quad (3)$$

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where we have used [2]

$$BR(\chi_{c0}(1P)\to\gamma \mathrm{J}/\psi(1S))=(1.27\pm0.06)\%,$$
$$BR(\chi_{c2}(1P)\to\gamma \mathrm{J}/\psi(1S))=(19.2\pm0.7)\%. \quad (4)$$

According to QCD, the decay of charmonium is due to the annihilation of the $c\bar{c}$ pair. The mass of $c\bar{c}$ is large and $c\bar{c}\to$ gluons are perturbative, so two-gluon decay mode is dominant. In the above equations, we did not use $\eta_c(2S)$ as an argument. Its hadronic decay channels are not well determined yet, and also the only measured radiative channel, $\eta_c(2S)\to\gamma\gamma$, suffers from very large uncertainty.

We know that

$$\begin{aligned}&\Gamma(\chi_{c2}(2P)\to\gamma\gamma)BR(\chi_{c2}(2P)\to \mathrm{D}\bar{\mathrm{D}})\\ =\ &(0.24\pm0.05\pm0.04)\mathrm{keV}\ \ [3]\\ &\Gamma(\chi_{c2}(2P)\to\gamma\gamma)BR(\chi_{c2}(2P)\to \mathrm{D}\bar{\mathrm{D}})\\ =\ &(0.18\pm0.05\pm0.03)\mathrm{keV}\ \ [1]. \end{aligned} \quad (5)$$

The PDG average gives 0.21 ± 0.04 keV [2].

Taking into account $\Gamma(\chi_{c2}(2P))\approx24$ MeV [2], we find

$$BR(\chi_{c2}(2P)\to2\gamma)BR(\chi_{c2}(2P)\to \mathrm{D}\bar{\mathrm{D}})\approx10^{-5} \ \text{ or}$$
$$BR(\chi_{c2}(2P)\to2\gamma)BR(\chi_{c2}(2P)\to \mathrm{D}\bar{\mathrm{D}})\approx0.75\times10^{-5}. \quad (6)$$

Conservatively selecting from Eq. (3) the ratio of the two-gluon to two-photon widths of the charmonium decays to be around $(1/4)\times10^4$, we obtain

$$BR(\chi_{c2}(2P)\to2\mathrm{g})BR(\chi_{c2}(2P)\to \mathrm{D}\bar{\mathrm{D}})\approx0.025 \ \text{ or}$$
$$BR(\chi_{c2}(2P)\to2\mathrm{g})BR(\chi_{c2}(2P)\to \mathrm{D}\bar{\mathrm{D}})\approx0.019. \quad (7)$$

So we expect $BR(\chi_{c2}(2P)\to2\mathrm{g})\gtrsim(2\pm0.4)\%$ if the PDG has correctly identified the state.

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 expected that the difference in the radial wave functions of $\chi_{c2}(1P)$ and $\chi_{c2}(2P)$ does not lead to a significant difference in $\Gamma(\chi_{c2}(1P)\to\gamma\gamma)$ and $\Gamma(\chi_{c2}(2P)\to\gamma\gamma)$. Indeed, $\Gamma(\chi_{c2}(1P)\to\gamma\gamma)\approx0.5$ keV [2] and $\Gamma(\chi_{c2}(2P)\to\gamma\gamma)\gtrsim0.24$ keV or 0.18 keV, cf. Eq. (5). That is to say, it is possible that $\Gamma(\chi_{c2}(2P)\to\gamma\gamma)\approx0.5$ keV because of the $\mathrm{D}\bar{\mathrm{D}}^*+\bar{\mathrm{D}}\mathrm{D}^*$ channel, which can be essential. For example, assuming $BR(\chi_{c2}(2P)\to \mathrm{D}\bar{\mathrm{D}})\approx BR(\chi_{c2}(2P)\to \mathrm{D}\bar{\mathrm{D}}^*+\bar{\mathrm{D}}\mathrm{D}^*)$, then $\Gamma(\chi_{c2}(2P)\to\gamma\gamma)\gtrsim0.48$ keV or 0.36 keV. It is also clear that such a consideration may take place for $\Gamma(\chi_{c2}(1P)\to2\mathrm{g})$ and $\Gamma(\chi_{c2}(2P)\to2\mathrm{g})$, which results in $\Gamma(\chi_{c2}(2P)\to2\mathrm{g})\approx\Gamma(\chi_{c2}(1P)\to2\mathrm{g})=\Gamma(\chi_{c2}(1P))(1-BR(\chi_{c2}(1P)\to\gamma \mathrm{J}/\psi(1S))\approx1.56$ MeV. We then obtain $BR(\chi_{c2}(2P)\to2\mathrm{g})\approx6.5\%$. In fact, the mass difference for $\chi_{c2}(2P)$ and $\chi_{c2}(1P)$ can be considered. In Ref. [8] the heavy quark mass m_{Q} is used in the non-relativistic limit, and instead, the meson mass M is adopted in Ref. [7], which leads to the difference of 30%. Guided by this estimate, we will write $\Gamma(\chi_{c2}(2P)\to2\gamma)\approx(0.5\pm0.2)$ keV, and $BR(\chi_{c2}(2P)\to2\mathrm{g})\approx(6.5\pm2.0)\%$. The current measurements have uncertainties with similar size. Then we note that our such observations and results agree very well with an explicit calculation from a heavy quark potential derived from the instanton vacuum along with the Coulomb and linear confinement potential [9].

3 Conclusion and outlook

Once the Particle Data Group as well as the BaBar and Belle collaborations have correctly identified the $\chi_{c2}(2P)$ state, there will be a very clean and reliable constraint of $BR(\chi_{c2}(2P)\to\mathrm{gluon\,gluon})\gtrsim2\%$ considering the leading-order property of the Charmonium decay. It is likely that $BR(\chi_{c2}(2P)\to2\mathrm{g})\approx(6.5\pm2.0)\%$.

The confirmation of the $\chi_{c2}(2P)$ state can be tested by BESIII, for example, through the process $\mathrm{e}^+\mathrm{e}^-\to\psi(4040)\to\gamma\chi_{c2}(2P)$ using their data above the center of mass of 4 GeV, as in their detector the two Ds can be clearly reconstructed. The search for two-gluon decays of the $\chi_{c2}(2P)$ state is feasible for BESIII as well as other super factories such as BaBar and Belle.

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