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On Trigluonia in Charmonium Physics

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Abstract

We discuss the search for a 1^{--} gluonium state, $\mathcal{O}$, in connection with a possible solution for the so called $\rho\pi, K^*\bar{K}$ puzzle in the J/ψ and ψ' decays. Some issues are examined. In particular, we argue that the expected most favorable process $\psi' \to \pi\pi\mathcal{O}$ can have an appreciable branching ratio only if the $\mathcal{O}$ has a decay width to $\rho\pi$ much narrower than normal hadronic widths. For the 0^{-+} system we deduce a relation that $BR(\eta_c' \to h) \approx BR(\eta_c \to h)$, where h denotes an exclusive light hadronic channel. This relation may be useful for the experimental search of the yet to be confirmed η_c' state, for which the branching ratios of $\psi' \to \gamma\eta_c' \to \gamma K\bar{K}\pi, \gamma\eta\pi\pi, \gamma\eta'\pi\pi$ are estimated to be about 1×10^{-4}, and this relation may also serve as a criterion to determine whether there exist anomalous decays in the η_c and η_c' system, in particular in the VV decay channels, which might be related to the 0^{-+} glueballs. We emphasize that the bigluonium and the trigluonium may have very different effects on these decays.

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Glueballs, especially the 1^{--} and 0^{-+} trigluonium states may play important roles in charmonium physics.

The search for a vector gluonium $\mathcal{O}$ with $J^{PC} = 1^{--}$ is particularly exciting and clear-cut. A large body of theoretical estimates[1] favor such a state around $2.4-2.5\ GeV$, though a much higher value of $4\ GeV$ has been proposed by a British Collaboration[2]. As pointed out by Hou and Soni[1,3] a vector gluonium is considerably cleaner to find than gluonia with other quantum numbers say $J^{PC} = 0^{++}, 0^{-+}$, or 2^{++}, because its mixing with quarkonia proceeds through $O(\alpha_s^3)$ for the interesting trigluonia case, rather than of $O(\alpha_s^2)$ and so in general the mixing is

much less, if the $\mathcal{O}$ and the vector quarkonium are not degenerate in mass. Therefore, whereas a vector quarkonium can be produced rather abundantly in e^+e^- annihilation through one-photon exchange, the cross section for producing a vector gluonium is exceedingly small[4], unless they are degenerate in mass and are consequently mixed substantially with each other.

An $\mathcal{O}$ at say 2.5 GeV can actually best be searched for in both

$$\psi' \to \pi\pi\mathcal{O}(\to \rho\pi), \quad J/\psi \to \pi\pi\mathcal{O}(\to \rho\pi). \tag{1}$$

For $\mathcal{O}$ of mass around 3 GeV, only $\psi' \to \pi\pi\mathcal{O}$ is allowed.

Though the $\mathcal{O}$ (Omicron) exists in its own right, attempts have been made to relate it to the outstanding puzzle of charmonium physics, namely the absence of ψ' decays to vector-pseudoscalar light hadrons. Here it is well known that one expects $J/\psi(\psi')$ to decay to light hadrons via three gluons, or occasionally via a single direct photon. In either case the decay proceeds via $|\Psi(0)|^2$, where $\Psi(0)$ is the wavefunction at the origin in the nonrelativistic quark model for $c\bar{c}$. But it is also known that for a ψ particle the leptonic width $\Gamma(\psi \to e^+e^-)$ is also proportional to $|\Psi(0)|^2$. Therefore it is reasonable to expect on the basis of perturbative QCD that for any hadronic final state h, we have

$$Q_h \equiv \frac{B(\psi' \to h)}{B(J/\psi \to h)} \approx \frac{B(\psi' \to e^+e^-)}{B(\psi \to e^+e^-)} = 0.128. \tag{2}$$

Usually this is true, and is well documented[5] for $p\bar{p}\pi^0, 2\pi^+2\pi^-\pi^0, \pi^+\pi^-\omega^0, 3\pi^+3\pi^-\pi^0$ hadronic channels. The startling exceptions occur for $\rho\pi$ and $K^*\bar{K}$, where the present experimental limits for $\rho\pi$[6],and $K^*\bar{K} + c.c.$[7] are

$$Q_{\rho\pi} < 0.0048, \quad Q_{K^{+*}K^{-}+c.c} < 0.0036. \tag{3}$$

Hou and Soni suggested a $J/\psi - \mathcal{O}$ mixing model to solve this puzzle[3]. Brodsky et al.[5] proposed a coherent explanation of the puzzle by assuming that the violation of the perturbative QCD theorem[8] that total hadron helicity is conserved in high-momentum-transfer exclusive processes when J/ψ decay to hadrons via three hard gluons is modulated by the gluons forming an intermediate gluonium 1^{--} state, the Omicron $\mathcal{O}$, before transition to hadrons h. It is the $\mathcal{O}$ which does not respect the helicity theorem, and accounts for the relatively large branching ratios (of order 10^{-2}) for $J/\psi \to \rho\pi, K^*\bar{K} + c.c.$. To account for the constraints (3), the $\mathcal{O}$ has a mass within 80 MeV/c^2 of the J/ψ mass, and total width smaller than 160 MeV. Concerning these explanations, there are, however, some problems which need to be clarified.

Here we discuss following issues which are concerned also by other authors if the Omicron $\mathcal{O}$ is indeed the solution to the puzzle (3). Let us assume that the J/ψ has an "$\mathcal{O}$" component via which J/ψ decays to $\rho\pi, K^*\bar{K}, \cdots$, then

$$|J/\psi >= \cos\theta|c\bar{c}, 1S > + \sin\theta|O >, \tag{4}$$

$$\Gamma(J/\psi \to \rho\pi) = \sin^2\theta \;\; \Gamma(\mathcal{O} \to \rho\pi) = (1.1 \pm 0.1)\ keV.^{[7]} \tag{5}$$

Using (4) and (5) we examine the following issues:

1. Mass degeneracy and large mixing. If the $\mathcal{O}$ is very close in mass to the J/ψ, then a large mixing between $\mathcal{O}$ and J/ψ might be possible. In fact, this possibility has been suggested by some authors[5,9], e.g., to explain the observed suppression of $J/\psi \to \gamma + \eta_c$ (a factor of 2 to 3 smaller than some theoretical expectations e.g. by the nonrelativistic potential model, and by the QCD sum rules)[9]. If we naively take an extreme case say, $\sin^2\theta = 0.5$ (accordingly, the calculated nonrelativistic M1 transition rate of $J/\psi \to \gamma\eta_c$ would be suppressed by a factor of 2 and thus compatible with data), then from (5) we would get $\Gamma(\mathcal{O} \to \rho\pi) \simeq 2\ keV$. Since $\rho\pi$ and other V P states are assumed to be dominant decay modes of the $\mathcal{O}$, as required by explain ing the $\rho\pi$ and other VP enhancement of J/ψ, the $\mathcal{O}$ would have a

total width of at most the order of a few 10 keV, being a very narrow resonance and thus distinguishable from other hadronic states. In this kind of cases, through a large mixing with J/ψ, the $\mathcal{O}$ would have a large leptonic

decay width, say order of 1 keV, then it should have been seen in $e^+e^- \to hadrons$ in the vicinity of J/ψ. However, the $\rho\pi$ channel has been carefully scanned across the J/ψ region in e^+e^- annihilation at BEPC (Beijing Electron-Positron Collider), but no hints of $\mathcal{O}$ are found[6]. Aside from this negative experimental result, there are many theoretical reasons which disfavor this large mixing case. For example, such an extremely narrow glueball width is unexpected; A larg e glueball component in the J/ψ would make J/ψ to be much more easily produced in the gluon fusion process in hadronic collisions; The large $\mathcal{O} - J/\psi$ (but not $\mathcal{O} - \psi'$) mixing would suppress $\Gamma(J/\psi \to e^+e^-)$ relative to $\Gamma(\psi' \to e^+e^-)$, because the glueball component almost decouples from the photon, it is then difficult to make the ratio $\frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)}$ agree with the data [note that QCD radiative corrections, which may obscure the theoretical estimation for the leptonic widths themselves, cancel out in this ratio]. Whereas this ratio can be well explained in the standard charmonium model. Therefore, we may conclude that the large $\mathcal{O} - J/\psi$ mixing is very unlikely.

2. Small mixing. Glueballs may be expected to have hadronic widths between OZI allowed and OZI suppressed widths. Therefore, it is plausible to have $\Gamma(\mathcal{O} \to \rho\pi) = (1-10)\ MeV$, and then from (5) $\sin^2\theta$ will be 10^{-3} to 10^{-4}. In this small mixing case, $\mathcal{O}$ would of course have very small leptonic width $\Gamma(\mathcal{O} \to e^+e^-) \simeq \sin^2\theta\Gamma(J/\psi \to e^+e^-) \simeq (10^{-3}-10^{-4})\times 5\ keV$ (assuming that $\mathcal{O}$ mixes only with J/ψ) and thus consistent with Hou and Soni[1]. Of course in general $\mathcal{O}$ may also mix with ω, ϕ, and other light vector mesons. The mixing angles are expected to be proportional to α_s^3, and to the wavefunction at origin of the meson. If $\mathcal{O}$ is very close to J/ψ[5], we might neglect the mixing between $\mathcal{O}$ and other light mesons. In this case, via the $\mathcal{O}$-J/ψ mixing, the $\psi' \to \pi\pi\mathcal{O}$ decay can proceed through $\psi' \to \pi\pi J/\psi$, which is the dominant decay mode of ψ' (with a branching ratio of about 50%) and is expected to be governed by the heavy quark transition via emitting two gluon continuum which are subsequently hadronized into two pions[17]. Note that in hadronic transitions for both the $c\bar{c}$ and $b\bar{b}$ states there seem no signs for resonances in the $\pi\pi$ system. Moreover, in J/ψ radiative decays neither $f_0(975)$ nor $f_0(1400)$ nor any other 0^{++} resonances have been observed experimentally in the $J/\psi \to \gamma\pi\pi$ decay[7], which is expected to proceed via $J/\psi \to \gamma gg \to \gamma\pi\pi$. This may suggest that below 1.5 GeV there exist no 0^{++} resonances which couple strongly to both two gluons and two pions. In this case, the two pions in $\psi' \to \pi\pi\mathcal{O}$ will come from the gluon continuum even if

the mass of $\mathcal{O}$ is lowered to only 2.4 GeV, and we then expect

$$B(\psi' \to \pi\pi\mathcal{O}) = \sin^2\theta B(\psi' \to \pi\pi J/\psi) \cdot \textit{phase space correction}, \tag{6}$$

which will be of order $10^{-3} - 10^{-4}$. Here the phase space correction can enhance this branching ratio by a factor larger than one but less than ten if the $\mathcal{O}$ should lie in the mass range 2.4-3.0 GeV.

If the $\mathcal{O}$ has a normal hadronic width to $\rho\pi$, say $\Gamma(\mathcal{O} \to \rho\pi) \simeq 50\ MeV$[1,3], then from (5) $\sin^2\theta = 2 \times 10^{-5}$, which leads to $B(\psi' \to \pi\pi\mathcal{O}) = O(10^{-5} - 10^{-4})$. Note that this value is much smaller than $1 - 2\%$ predicted by Hou and Soni[1,3]. The main source of such a huge difference in the predicted rate might be that our estimated $\mathcal{O} - J/\psi$ mixing angle is very small, and also because we do not take the enhancement effect of a suggested 0^{++} glueball[1,3] into account. If our estimate makes sence it would be very difficult to find $\mathcal{O}$ in $\psi' \to \pi\pi\mathcal{O}$, if $\mathcal{O}$ has a normal hadronic decay width to $\rho\pi$.

We may then conclude that only if the $\mathcal{O}$ has a decay width to $\rho\pi$ much narrower than normal hadronic widths, the $\psi' \to \pi\pi\mathcal{O}$ decay can have an appreciable branching ratio.

Another question is that for such a heavy particle $\mathcal{O}$ of 3 GeV, unlike say the ω, many decay channels are open, and the mystery is then why should the $\rho\pi$, $K^*\bar{K}$, and other VP channels dominate amongst decays of $\mathcal{O}$. Historically the existence of such a gluonium was first postulated by Freund and Nambu[10] (with an estimated mass of only 1.4 to 1.8 GeV) based on OZI dynamics. Indeed they did predict that the $\mathcal{O}$ would decay copiously into $\rho\pi$, $K^*\bar{K}$ by assuming ideal mixing with the ground state $I = 0$ ω, ϕ, and J/ψ (but not with radially excited ψ'). However it is far from clear that this dynamics can be extrapolated to cover the needs of an $\mathcal{O}$ at 3 GeV with small mixing to the J/ψ.

3. Mystery of the $J/\psi \to \omega\pi^0$ mode. Here an isospin changing process is involved, probably with the three-gluons exchange replaced by a highly virtual photon. Brodsky[11] pointed out that $J/\psi \to \omega\pi^0$ is of order three times the electromagnetic transition $J/\psi \to \pi^+\pi^-$. For helicity theorem[8] to be valid at the J/ψ mass scale, we need to invoke a nearby hybrid $q\bar{q}g$ state for this $I = 1$ transition in addition to $\mathcal{O}$ (or perhaps regard $\mathcal{O}$ as the $I = 0$ piece of $q\bar{q}g$) and the situation becomes clearly more contrived. Also, the $\rho - \omega$ mixing model can not give the large rate of $J/\psi \to \omega\pi^0$ through $J/\psi \to \rho^0\pi^0 \to \omega\pi^0$, because experimentally the rate of $J/\psi \to \omega\pi^0$ is as large as 0.1 times the rate of $J/\psi \to \rho^0\pi^0$[7], whereas the effect of the $\rho - \omega$ mixing is only of order 10^{-2} (note that, e.g., the branching ratio of $\omega \to \pi^+\pi^-$ is about 2%). If the puzzle (3) is to be sought outside[12,13] of the Omicron model (and hence no commitment to the helicity theorem[8]), it would be quite interesting to measure the branching ratios for both $\psi' \to \omega\pi^0$ and $\pi^+\pi^-$. If both channels obey relation(2), they are likely to be purely electromagnetic decays, and this would imply the failure of the helicity theorem at this energy scale. If, however, the $\omega\pi^0$ mode of ψ' is substantially suppressed than that given by (2), then it might have some peculiar hadronic nature.

Next, we will turn into the pseudoscalar sector, discussing possible connections between the η_c, η_c' mesons and the 0^{-+} glueballs. We will put stress on the yet to be confirmed η_c' meson.

The search for the η_c' is particularly interesting not only for it is an important member to be confirmed in the charmonium family, but also because it could shed light on the puzzle

in the J/ψ and ψ' decays. Indeed, if something anomalous happens between J/ψ and ψ', it might also happen between their spin-singlet partners η_c and η_c'.

Anselmino et al.[14] extended the Brodsky et al. model[5] to the $\eta_c(2980)$ situation, where they noted that the decays $\eta_c \to \rho\rho, K^*\bar{K}^*, \phi\phi, p\bar{p}$ have also relatively large branching ratios even though these modes are all first-order forbidden by hadron helicity conservation in perturbative QCD. They wish to suggest here that this situation can once again be attributed to the presence of a trigluonium, this time in the pseudoscalar 0^{-+} state, with a mass close (within 60 MeV) to the η_c. In order to distinguish the normal case from the case where there exists the $\eta_c - glueball$ mixing, they assume[15] for any normal light hadronic channel h

$$\frac{B(\eta_c' \to h)}{B(\eta_c \to h)} \approx \frac{B(\psi' \to h)}{B(J/\psi \to h)} = 0.128 \tag{7}$$

and argue that such an assumption is rather plausible given that $M_{\eta_c'} - M_{\eta_c} \simeq M_{\psi'} - M_{J/\psi}$.

In contrast to Anselmino et al., we argue that, unlike the ψ', J/ψ case (2), the branching ratio relationship for η_c' and η_c to a light hadronic channel h is

$$\frac{B(\eta_c' \to h)}{B(\eta_c \to h)} \approx 1. \tag{8}$$

The argument is as follows. First, analogous to J/ψ, ψ', we have

$$\frac{\Gamma(\eta_c' \to h)}{\Gamma(\eta_c \to h)} \approx \frac{[|\psi(0)|/M]^2_{\eta_c'}}{[|\psi(0)|/M]^2_{\eta_c}} \tag{9}$$

via the two-gluon intermediary to any normal light hadron final state h. For η_c as the lightest $c\bar{c}$ state, the relation

$$\Gamma_{tot}(\eta_c) \approx \Gamma(\eta_c \to 2g) = \frac{8\alpha_s^2|R(0)|^2_{\eta_c}}{3M^2_{\eta_c}}(1 + 4.8\frac{\alpha_s}{\pi}) \tag{10}$$

holds in the nonrelativistic limit, where $R(0)$ is the radial wavefunction for η_c and where the QCD radiative correction factor is included[16], and we assume for $2g \to hadrons$ the hadronization factor to be of unity. For η_c', we assert that here also

$$\Gamma_{tot}(\eta_c') \approx \Gamma(\eta_c' \to 2g) = \frac{8\alpha_s^2|R(0)|^2_{\eta_c'}}{3M^2_{\eta_c'}}(1 + 4.8\frac{\alpha_s}{\pi}). \tag{11}$$

Accepting (11) together with (10) and (9) then statement (8) is established. The task is then to justify (11).

Let us digress and review the situation in ψ'. Here

$$\begin{aligned}\Gamma_{tot}(\psi') &= \Gamma(\psi' \to J/\psi + \pi + \pi) + \Gamma(\psi' \to J/\psi + \eta) + \Gamma(\psi' \to \gamma + \chi_{c0}) \\ &+\Gamma(\psi' \to \gamma + \chi_{c1}) + \Gamma(\psi' \to \gamma + \chi_{c2}) + \Gamma(\psi' \to 3g).\end{aligned} \tag{12}$$

However, $\Gamma_{tot}(\psi')$ is dominated by $\psi' \to J/\psi + \pi + \pi$ and $\psi' \to \gamma + \chi_{cJ}$, not by $\psi' \to 3g \to$ *light hadrons*, thus leading to (2).

For the η_c' case, we expect

$$\Gamma_{tot}(\eta_c') = \Gamma(\eta_c' \to \eta_c + \pi + \pi) + \Gamma(\eta_c' \to \psi(^1P_1) + \gamma) + \Gamma(\eta_c' \to J/\psi + \gamma) + \Gamma(\eta_c' \to 2g). \quad (13)$$

Let us estimate the individual terms on the r.h.s. of (13).

(i) $\Gamma(\eta_c' \to \eta_c + \pi + \pi)$ and $\Gamma(\psi' \to J/\psi + \pi + \pi)$ both preserve parity and C-parity of their $c\bar{c}$ piece in transition, and have comparable phase space. Hence $\Gamma(\eta_c' \to \eta_c + \pi + \pi) \approx \Gamma(\psi' \to J/\psi + \pi + \pi)$[17], and is thus equal to 140 keV[7].

(ii)The $E1$ transition width $\Gamma(\eta_c' \to \psi(^1P_1) + \gamma) = \frac{4}{3}e_c^2\alpha k^3 | <^1 P_1|r|\eta_c' > |^2$. Taking $M(^1P_1)$ at the c.o.g. of the $M(^3P_J)$ states, $M_{\eta_c'}$ at 3600 $MeV, k = 80$ MeV, and the dipole transition matrix element $| <^1 P_1|r|2S > | = 2$ to 3 GeV^{-1}, it is then estimated[18] that $\Gamma(\eta_c' \to \psi(^1P_1) + \gamma)$ is about 11 keV, certainly in the range $O(10)$ keV.

(iii) The $M1$ transition width $\Gamma(\eta_c' \to J/\psi + \gamma)$ has also been estimated[18], and is found to be about 5 keV hence in the range $O(1)$ keV.

(iv) $\Gamma(\eta_c' \to 2g)$ is estimated to be about 4 MeV by noting[18] that in the nonrelativistic limit with the hyperfine splitting effects neglected

$$\frac{\Gamma(\eta_c' \to 2g)}{\Gamma(\eta_c \to 2g)} = \frac{[|R(0)|/M]^2_{\eta_c'}}{[|R(0)|/M]^2_{\eta_c}} \approx \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)} \quad (14)$$

and using $\Gamma(\eta_c \to 2g) \simeq \Gamma_{tot}(\eta_c) = 10.3^{+3.8}_{-3.4}$ MeV[7] and the experimental values for the J/ψ and ψ' leptonic widths.

We find in conjunction with (13) and (i)-(iv) above, that

$$\Gamma_{tot}(\eta_c') \simeq \Gamma(\eta_c' \to 2g) = \Gamma(\eta_c' \to hadrons) \quad (15)$$

where $\Gamma(\eta_c' \to 2g)$ is estimated from (14) to be about 4 MeV, certainly in the range $1 - 10$ MeV, which is much greater than the widths of other decay channels, and hence is very much the dominant mode. Obviously, this overwhelming dominance is not affected by the possible uncertainties in estimates (i)-(iv). Therefore Eq.(8) is confirmed.

We emphasize that if (8) but not (7) is the counterpart of (2) for a normal hadronic channel, then the situation for searching for the η_c' will be much more optimistic. In particular, using (8) and the experimentally observed branching ratios of η_c[7], we will have

$$B(\eta_c' \to K\bar{K}\pi) \approx (6.6 \pm 1.8)\%, \quad (16)$$

$$B(\eta_c' \to \eta\pi\pi) \approx (4.9 \pm 1.8)\%, \quad (17)$$

$$B(\eta_c' \to \eta'(958)\pi\pi) \approx (4.1 \pm 1.7)\%, \quad (18)$$

since these decay channels are probably not helicity suppressed and therefore expected to satisfy (8). More interestingly, we would get

$$B(\eta_c' \to \rho\rho) \approx (2.6 \pm 0.9)\%, \quad (19)$$

$$B(\eta_c' \to K^*\bar{K}^*) \approx (0.85 \pm 0.31)\%, \tag{20}$$

$$B(\eta_c' \to \phi\phi) \approx (0.71 \pm 0.28)\%, \tag{21}$$

$$B(\eta_c' \to p\bar{p}) \approx (0.12 \pm 0.04)\%, \tag{22}$$

if these decay channels were not helicity suppressed and thus also satisfy (8). However, if the helicity conservation theorem is valid for both η_c and η_c', then the branching ratios of $\eta_c' \to VV$ will be much smaller than the values given in (19)-(22) and the violation of (8) in this case could be due to the anomalous enhancement of $\eta_c \to VV$ decay rates, which might come from a 0^{-+} glueball component in the η_c wave function.

Thus, the estimates in (16)-(18) and (19)-(22) for the η_c' decay rates, which are derived based on (8), can be useful in two respects.

First, the large branching ratios in (16)-(18) may indicate that through those channels in processes like $e^+e^- \to \psi' \to \gamma\eta_c' \to \gamma K\bar{K}\pi, \gamma\eta\pi\pi, \gamma\eta'\pi\pi$, and $p\bar{p} \to \eta_c' \to K\bar{K}\pi, \eta\pi\pi, \eta'\pi\pi$, the η_c' meson can be searched for experimentally. For instance, using (16)-(18) and the data of $J/\psi \to \gamma\eta_c$ decay[7], we get

$$B(\psi' \to \gamma\eta_c') \times B(\eta_c' \to K\bar{K}\pi) \approx 1.1 \times 10^{-4}, \tag{23}$$

$$B(\psi' \to \gamma\eta_c') \times B(\eta_c' \to \eta\pi\pi) \approx 0.8 \times 10^{-4}, \tag{24}$$

$$B(\psi' \to \gamma\eta_c') \times B(\eta_c' \to \eta'\pi\pi) \approx 0.7 \times 10^{-4}, \tag{25}$$

where we have assumed the $M1$ transition amplitude for $\psi' \to \gamma\eta_c'$ to be the same as that for $J/\psi \to \gamma\eta_c$, which is expected to hold in the nonrelativistic limit, and the mass of η_c' to be 3600 MeV [18], and hence

$$B(\psi' \to \gamma\eta_c') = \frac{\Gamma(J/\psi \to \gamma\eta_c)}{\Gamma_{tot}(\psi')} \cdot (\frac{k_{\eta_c'}}{k_{\eta_c}})^3 \approx 1.6 \times 10^{-3}, \tag{26}$$

with the emitted photon energy $k_{\eta_c} = 115\ MeV$ and $k_{\eta_c'} = 85\ MeV$. If the mass of η_c' is higher than 3600 MeV assumed here, the branching ratios will be lower than the values given in (26) and (23)-(25) accordingly. Moreover, (26) may also be subject to relativistic corrections. Nevertheless, the roughly estimated branching ratios in (23)-(25) are indeed encouraging experimentally in finding the η_c' meson, with, say, 5×10^6 to 1×10^7 ψ' events in the near future.

Second, if the branching ratios estimated in (19)-(22) for $\rho\rho, K^*\bar{K}^*, \phi\phi$, and $p\bar{p}$ are true experimentally, then the helicity conservation theorem will be in trouble; On the other hand, however, if the observed branching ratios are much lower than the values in (19)-(22), then the helicity conservation theorem will probably be correct, and the enhanced decay rates of η_c in these channels could be due to a 0^{-+} gluball component, which does not respect the helicity theorem, mixed into the η_c wave function. Therefore, (19)-(22) may serve as a criterion to check the validity of the helicity theorem, and to determine whether these channels are indeed anomalous.

Unlike the J/ψ, which can only mix with a 1^{--} trigluonium, the η_c may mix with both 0^{-+} trigluonium and bigluonium. In general, if the enhancement of these helicity suppressed decays are due to a mixed glueball component G, we will expect

$$\frac{B(\eta_c' \to VV)}{B(\eta_c \to VV)} = \frac{B(\eta_c' \to h)}{B(\eta_c \to h)} \cdot \frac{(M_{\eta_c} - M_G)^2 + (\Gamma_G/2)^2}{(M_{\eta_c'} - M_G)^2 + (\Gamma_G/2)^2}. \tag{27}$$

If the 0^{-+} bigluonium is the dominant glueball component mixed in the η_c and η_c' wave functions, then branching ratios of $\eta_c' \to VV$ from (27) will not be much smaller than that given in (19)-(22), because the mass of 0^{-+} bigluonium is expected to be below 2 GeV. It is quite possible that when the η_c decays predominantly into two gluons they may form an intermediate 0^{-+} bigluonium state before transition to hadrons. If we simply choose the $\eta(1440)$ (which was known as the $\iota(1440)$) as the candidate of the 0^{-+} bigluonium state (though far from being confirmed) then from (27) and (8) we will get

$$\frac{B(\eta_c' \to VV)}{B(\eta_c \to VV)} \approx 0.5. \tag{28}$$

(28) implies that there could be no much suppression for the $\eta_c' \to VV$ decays relative to that for the η_c, and both decays would be helicity suppressed but are possibly enhanced by the 0^{-+} bigluonium component. This possible scenario is very different from the $J/\psi \to VP$ and $\psi' \to VP$ decays, where the latter are much more suppressed than the former.

However, if the 0^{-+} trigluonium state lies very close to η_c, its mixing with η_c can be the dominant glueball component in η_c even though the 0^{-+} trigluonium-η_c coupling strength is weaker than the 0^{-+} bigluonium-η_c coupling strength due to the suppression of higher order of α_s. As in ref.[14], if we assume that the 0^{-+} trigluonium state has a mass within about 60 MeV from the η_c, and a width about 120 MeV, and is the only glueball component in the η_c, then from (27) and (8) we will get

$$B(\eta_c' \to \rho\rho) \leq 5 \times 10^{-4}, \tag{29}$$

$$B(\eta_c' \to K^*\bar{K}*) \leq 2 \times 10^{-4}, \tag{30}$$

$$B(\eta_c' \to \phi\phi) \leq 2 \times 10^{-4}, \tag{31}$$

$$B(\eta_c' \to p\bar{p}) \leq 3 \times 10^{-5}. \tag{32}$$

The estimated branching ratios in (29)-(32) are much smaller than that given in (19)-(22), but larger by almost an order of magnitude than predicted in ref.[14]. However, as we pointed out above, the 0^{-+} trigluonium and bigluonium may be competitive in mixing with η_c, and therefore the actual situation for the VV decay modes of η_c and η_c' could be more complicated. The bigluonium dominated case (28) and the trigluonium dominated case (29)-(32) are perhaps the two extreme cases. It will be interesting to examine the real situation by experiment in the search for the η_c' meson.

In summary, we have discussed the effects of 1^{--} and 0^{-+} gluonium states in connection with the J/ψ, ψ', and η_c, η_c' mesons. We discussed the search for the 1^{--} trigluonium state in connection with a possible solution for the so called $\rho\pi$ and K^*K puzzle in the J/ψ and

ψ' decays. We examined some issues and open questions. We emphasized that the mixing between J/ψ and the trigluonium $\mathcal{O}$ should be very small, and accordingly the branching ratio for the most favorable process $\psi' \to \pi\pi\mathcal{O}$ in searching for $\mathcal{O}$ is also very small unless the $\mathcal{O}$ has a very narrow width. We deduced a relation that $B(\eta_c' \to h) \approx B(\eta_c \to h)$ for a normal light hadronic channel h. Using this relation we estimated the branching ratios of $\psi' \to \gamma\eta_c' \to \gamma K\bar{K}\pi, \gamma\eta\pi\pi, \gamma\eta'\pi\pi$ to be about 1×10^{-4}. This relation may also be useful in determining whether there exist anomalous decays in the η_c and η_c' states, e.g., in the VV decay channels. Any substantial deviation from this relation might imply something anomalous. The existence of a glueball component in η_c or even in η_c' will be a very interesting possibility. If the bigluonium is the dominant glueball component mixed in η_c and η_c' then the VV decay branching ratios should not be much more suppressed for η_c' than for η_c, whereas in the case of trigluonium dominance, a severe suppression will occur. We hope the experimental study on the ψ' and η_c' (e.g. at BES/BEPC) will further clarify these issues and reveal the nature of the problems discussed above.

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Note added. After this work was submitted for publication we learned that there were similar discussions to our eqs.(4) and (5), i.e. the $\mathcal{O}$-J/ψ mixing and some related problems, by M.Anselmino et al., Turino preprint DFTT 64/93, hep-ph 9310344.

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