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Towards the nature of $X(3872)$ resonance

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Abstract: The spectra of decays of resonance $X(3872)$ with good analytical and unitary properties are constructed, which allows to define the branching ratio of the $X(3872) \to D^{*0}\overline{D}^0 + c.c.$ decay by studying only one more decay, for example, the $X(3872) \to \pi^+\pi^- J/\psi(1S)$ decay, and it is shown that the spectra are an effective means of selection of models for the resonance $X(3872)$. Then the scenario is discussed where the $X(3872)$ resonance is the $c\bar{c} = \chi_{c1}(2P)$ charmonium which "sits on" the $D^{*0}\overline{D}^0$ threshold. An explanation is given of the shift of the mass of the $X(3872)$ resonance with respect to the prediction of a potential model for the mass of the $\chi_{c1}(2P)$ charmonium by the contribution of the virtual $D^*\overline{D} + c.c.$ intermediate states into the self energy of the $X(3872)$ resonance. This allows us to estimate the coupling constant of the $X(3872)$ resonance with the $D^{*0}\overline{D}^0$ channel, the branching ratio of the $X(3872) \to D^{*0}\overline{D}^0 + c.c.$ decay, and the branching ratio of the $X(3872)$ decay into all non-$D^{*0}\overline{D}^0 + c.c.$ states. A significant number of unknown decays of $X(3872)$ via two gluons: $X(3872) \to$ *gluon gluon* $\to$ *hadrons* are predicted.

Key words: Charmonium; molecule; two-gluon decays

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走近 $X(3872)$ 共振态的本质

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摘要:构造了具有良好解析性和幺正性的共振态 $X(3872)$衰变谱,能够定义衰变反应 $X(3872) \to D^{*0}\overline{D}^0 + c.c.$ 的分支比,而只需要多研究另外一个衰变,比如说 $X(3872) \to \pi^+\pi^- J/\psi(1S)$ 衰变,这表明构造谱是筛选共振态 $X(3872)$模型的有效工具.之后讨论了共振态 $X(3872)$是粲偶素 $c\bar{c} = \chi_{c1}(2P)$的情形,此时它处在$D^{*0}\overline{D}^0$的阈上.根据由粲偶素$\chi_{c1}(2P)$的质量的势能模型的预言解释了共振态 $X(3872)$的质量偏移.这个势能模型是依据衰变产物$D^*\overline{D} + c.c.$ 的中间态计入共振态 $X(3872)$的质量的贡献而构造的.这使得我们能够研究共

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振态 $X(3872)$和衰变道$D^{*0}\overline{D}^0$的耦合常数，$X(3872)\to D^{*0}\overline{D}^0+c.c.$的衰变分支比以及共振态 $X(3872)$衰变到所有不含$D^{*0}\overline{D}^0+c.c.$的过程的分支比. 预言了一个共振态 $X(3872)$通过双胶子衰变的重要常数.
关键词：粲偶素；分子；双胶子衰变

0 Introduction

The $X(3872)$ resonance became the first in discovery of the resonant structures XYZ ($X(3872)$, $Y(4260)$, $Z_b^+(10610)$, $Z_b^+(10650)$, $Z_c^+(3900)$), the interpretations of which as hadron states assumes existence in them at least pair of heavy and pair of light quarks in this or that form.

Thousands of articles on this subject have been published in spite of the fact that many properties of new resonant structures are not defined yet and not all possible mechanisms of dynamic generation of these structures are studied, in particular, the role of the anomalous Landau thresholds is not yet studied. Consequently, this spectroscopy took the central place in the physics of hadrons.

Below we give reasons that $X(3872)$, $I^G(J^{PC})=0^+(1^{++})$, is the $\chi_{c1}(2P)$ charmonium and suggest a physically clear program of experimental researches for the verification of our assumption.

1 How to learn the branching ratio $X(3872)\to D^{*0}\overline{D}^0+c.c.$ [1]

The mass spectrum $\pi^+\pi^-J/\psi(1S)$ looks like the ideal Breit-Wigner one in the $X(3872)\to\pi^+\pi^-J/\psi(1S)$ decay, see Fig. 1(a).

The mass spectrum $\pi^+\pi^-\pi^0\ J/\psi(1S)$ in the $X(3872)\to\pi^+\pi^-\pi^0\ J/\psi(1S)$ decay looks similar[3-4]. The mass spectrum $D^{*0}\overline{D}^0+c.c.$ in the $X(3872)\to D^{*0}\overline{D}^0+c.c.$ decay[5] looks like the typical resonance threshold enhancement, see Fig. 2.

If structures in the above channels are a manifestation of the same resonance, it is possible to define the branching ratio $BR(X(3872)\to D^{*0}\overline{D}^0+c.c.)$ treating data of the two above decay channels only.

We believe that the $X(3872)$ is the axial vector, 1^{++}[6-7]. In this case the S wave dominates in the $X(3872)\to D^{*0}\overline{D}^0+c.c.$ decay and hence is described by the effective Lagrangian

$$L_{XD^{*0}D^0}(x)=g_AX^\mu(D^0_\mu(x)\overline{D}^0(x)+\overline{D}^0_\mu(x)D^0(x)) \quad (1)$$

The width of the $X\to D^{*0}\overline{D}^0+c.c.$ decay

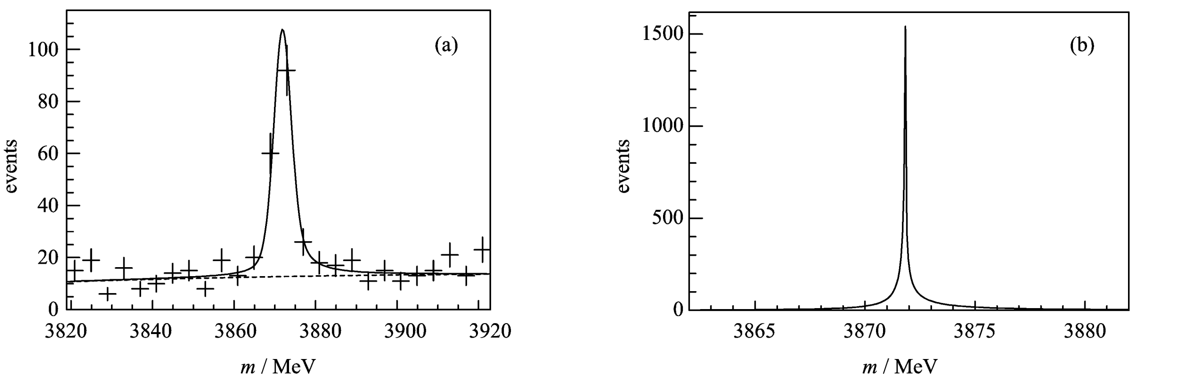
$$\Gamma(X\to D^{*0}\overline{D}^0+c.c.,m)=\frac{g_A^2}{8\pi}\frac{\rho(m)}{m}\left(1+\frac{\boldsymbol{k}^2}{3m^2_{D^{*0}}}\right) \quad (2)$$

where $\boldsymbol{k}$ is the momenta of D^{*0} (or $\overline{D}^0$) in the $D^{*0}\overline{D}^0$ center mass system, and m is the invariant mass of the $D^{*0}\overline{D}^0$ pair,

$$\rho(m)=\frac{2\,|\,\boldsymbol{k}\,|}{m}=\frac{\sqrt{(m^2-m^2_+)(m^2-m^2_-)}}{m^2},$$

$$m_\pm=m_{D^{*0}}\pm m_{D^0}.$$

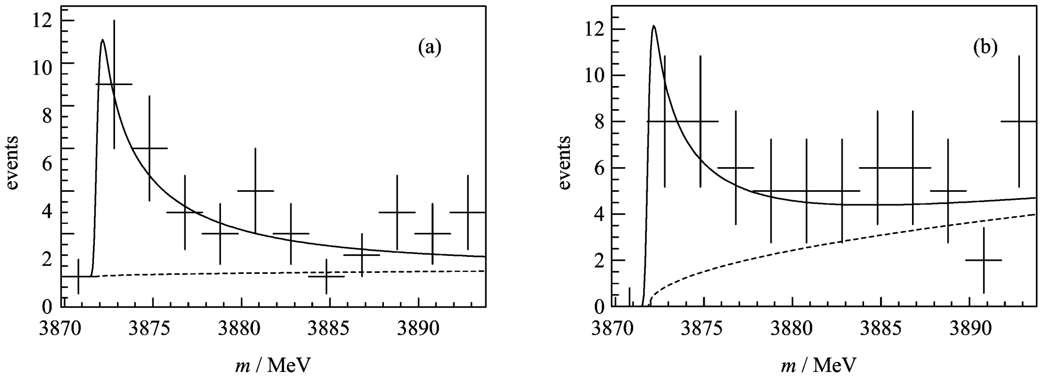
The second term in the right side of Eq. (2) is very small in our energy region and can be



The solid line is our theoretical one taking into account the Belle energy resolution.

The dotted line is the second-order polynomial for the incoherent background.

Fig. 1　The Belle data[2] on the invariant $\pi^+\pi^-J/\psi(1S)$ mass (m) distribution (a) and our undressed theoretical line (b)



(a) $D^{*0} \to D^0\pi^0$ (b) $D^{*0} \to D^0\gamma$

The solid line represents our theoretical prediction taking into account the Belle energy resolution.
The dotted line is a square root function for the incoherent background.

Fig. 2 The Belle data[5] on the invariant $D^{*0}\overline{D}^0 + c.c.$ mass (m) distribution

neglected. This gives us an opportunity to construct the mass spectra for the $X(3872)$ decays with the good analytical and unitary properties as in the scalar meson case[8-9].

The mass spectrum in the $D^{*0}\overline{D}^0+c.c.$ channel

$$\frac{\mathrm{d}BR(X\to D^{*0}\overline{D}^0+c.c.,m)}{dm} = 4\frac{1}{\pi}\frac{m^2\Gamma(X\to D^{*0}\overline{D}^0,m)}{|D_X(m)|^2} \quad (3)$$

The branching ratio of $X(3872)\to D^{*0}\overline{D}^0+c.c.$

$$BR(X\to D^{*0}\overline{D}^0+c.c.) = 4\frac{1}{\pi}\int_{m_+}^{\infty}\frac{m^2\Gamma(X\to D^{*0}\overline{D}^0,m)}{|D_X(m)|^2}\mathrm{d}m \quad (4)$$

In other $\{i\}$ (non-$D^{*0}\overline{D}^0$) channels the $X(3872)$ state is seen as a narrow resonance, which is why we write the mass spectrum in the i channel in the form

$$\frac{\mathrm{d}BR(X\to i,m)}{\mathrm{d}m} = 2\frac{1}{\pi}\frac{m_X^2\Gamma_i}{|D_X(m)|^2} \quad (5)$$

where Γ_i is the width of the $X(3872)\to i$ decay.

The branching ratio of $X(3872)\to i$

$$BR(X\to i) = 2\frac{1}{\pi}\int_{m_0}^{\infty}\frac{m_X^2\Gamma_i}{|D_X(m)|^2}\mathrm{d}m \quad (6)$$

where m_0 is the threshold of the i channel.

The inverse propagator $D_X(m)$

$$D_X(m) = m_X^2 - m^2 + Re(\Pi_X(m_X^2)) - \Pi_X(m^2) - \imath m_X\Gamma \quad (7)$$

where $\Gamma=\Sigma\Gamma_i<1.2$ MeV is the total width of the $X(3872)$ decay into all non-($D^{*0}\overline{D}^0+c.c.$) channels.

$$\Pi_X(s) = \frac{g_A^2}{8\pi^2}\left(I^{D^{*0}\overline{D}^0}(s) + I^{D^{*+}D^-}(s)\right),\ m^2 = s \quad (8)$$

When $m_+=m_{D^*}+m_D\leqslant m$,

$$I^{D^*\overline{D}}(m^2) = \frac{(m^2-m_+^2)}{m^2}\frac{m_-}{m_+}\ln\frac{m_{D^*}}{m_D} + \rho(m)\left[\imath\pi + \ln\frac{\sqrt{m^2-m_-^2}-\sqrt{m^2-m_+^2}}{\sqrt{m^2-m_-^2}+\sqrt{m^2-m_+^2}}\right] \quad (9)$$

where $m_-=m_{D^*}-m_D$.

When $m_-\leqslant m\leqslant m_+$,

$$I^{D^*\overline{D}}(m) = \frac{(m^2-m_+^2)}{m^2}\frac{m_-}{m_+}\ln\frac{m_{D^*}}{m_D} - 2|\rho(m)|\arctan\frac{\sqrt{m^2-m_-^2}}{\sqrt{m_+^2-m^2}} \quad (10)$$

where $|\rho(m)|=\sqrt{(m_+^2-m^2)(m^2-m_-^2)}/m^2$.

When $m\leqslant m_-$ and $m^2\leqslant 0$,

$$I^{D^*\overline{D}}(m) = \frac{(m^2-m_+^2)}{m^2}\frac{m_-}{m_+}\ln\frac{m_{D^*}}{m_D} - \rho(m)\ln\frac{\sqrt{m_+^2-m^2}-\sqrt{m_-^2-m^2}}{\sqrt{m_+^2-m^2}+\sqrt{m_-^2-m^2}} \quad (11)$$

Our branching ratios satisfy the unitarity

$$1 = BR(X\to D^{*0}\overline{D}^0+c.c.) + BR(X\to D^{*+}\overline{D}^-+c.c.) + \sum_i BR(X\to i) \quad (12)$$

Fitting the Belle data[2], we take into account the Belle results[2]: $m_X=3\,871.84$ MeV$=m_{D^{*0}}+m_{D^0}=m_+$ and $\Gamma_{X(3872)}<1.2$ MeV 90% CL, that corresponds to $\Gamma<1.2$ MeV, which controls the width of the $X(3872)$ signal in the $\pi^+\pi^- J/\psi(1S)$ channel and in every non-$(D^{*0}\overline{D}^0+c.c.)$ channel. The results of our fit are in the Tab. 1.

Tab. 1 BR_{seen} is a branching ratio for $m\leqslant 3\,891.84$ MeV, Γ in MeV, g_A in GeV

Γ	$1.2_{-0.4}$	mode	$D^{*0}\overline{D}^0+c.c.$	$D^{*+}D^-+c.c.$	Others
$g_A^2/8\pi$	1.4^{+5}_{-1}	BR	$0.6^{+0.02}_{-0.1}$	$0.31^{+0.13}_{-0.16}$	$0.1^{+0.3}_{-0.1}$
χ^2/Ndf	45/42	BR_{seen}	$0.3^{+0.1}_{-0.2}$	$0.03^{+0.004}_{-0.02}$	$0.09^{+0.3}_{-0.1}$

Our approach can serve as a guide to the selection of theoretical models for the $X(3872)$ resonance. Indeed, if $3\,871.68$ MeV $< M_X <$ $3\,871.95$ MeV and $\Gamma_{X(3872)}=\Gamma<1.2$ MeV then for $g_A^2/4\pi<0.2$ GeV^2 $BR(X\to D^{*0}\overline{D}^0+c.c.;\ m\leqslant 3\,891.84\ \text{MeV})<0.3$. That is, unknown decays of $X(3872)$ into non-$D^{*0}\overline{D}^0$ states are considerable or dominant.

For example, in Ref. [10] the authors considered $m_X=3\,871.68$ MeV, $\Gamma=1.2$ MeV and $g_{XDD^*}=g_A\sqrt{2}=2.5$ GeV, that is, $g_A^2/8\pi=0.1$ GeV^2. In this case $BR(X\to D^{*0}\overline{D}^0+c.c.)\approx 0.2$, that is, unknown decays $X(3872)$ into non-$(D^{*0}\overline{D}^0+c.c.)$ states are dominant. For details see Tab. 2.

Tab. 2 Branching ratios for the model from Ref. [10]

m_X	3 871.68	mode	$X\to D^{*0}\overline{D}^0+c.c.$	$X\to D^{*+}D^-+c.c.$	$X\to$ Others
Γ	1.2	BR	0.176	0.045	0.779
$g_A^2/8\pi$	0.1	BR_{seen}	0.14	0.011	0.761

【Note】 Γ in MeV, m_X in MeV, g_A in GeV

2 $X(3872)$, $I^G(J^{PC})=0^+(1^{++})$, as the $\chi_{c1}(2P)$ charmonium[11]

Contrary to the almost standard opinion that the $X(3872)$ resonance is the $D^{*0}\overline{D}^0+c.c.$ molecule or the $qc\bar{q}\bar{c}$ four-quark state, we discuss the scenario where the $X(3872)$ resonance is the $c\bar{c}=\chi_{c1}(2P)$ charmonium which "sits on" the $D^{*0}\overline{D}^0$ threshold.

The two dramatic discoveries have generated a stream of the $D^{*0}\overline{D}^0+D^0\overline{D}^{*0}$ molecular interpretations of the $X(3872)$ resonance.

The mass of the $X(3872)$ resonance is 50 MeV lower than predictions of the most lucky naive potential models for the mass of the $\chi_{c1}(2P)$ resonance,

$$m_X-m_{\chi_{c1}(2P)}=-\Delta\approx-50\ \text{MeV} \qquad (13)$$

and the relation between the branching ratios

$$BR(X\to\pi^+\pi^-\pi^0 J/\psi(1S))\approx BR(X\to\pi^+\pi^- J/\psi(1S)) \qquad (14)$$

that is interpreted as a strong violation of isotopic symmetry.

But the bounding energy is small, $\epsilon_B<(1\sim3)$ MeV. That is, the radius of the molecule is large, $r_{X(3872)}>(3\sim5)$ fm $=(3\sim5)\times10^{-13}$ cm. As for the charmonium, its radius is less one fermi, $r_{\chi_{c1}(2P)}\approx 0.5$ fm $=0.5\times10^{-13}$ cm. That is, the molecule volume is $100\sim1\,000$ times as large as the charmonium volume, $V_{X(3872)}/V_{\chi_{c1}(2P)}>100\sim1\,000$.

How to explain sufficiently abundant inclusive production of the rather extended molecule X(3872) in a hard process $pp\to X(3872)+anything$ with rapidity in the range $2.5\sim4.5$ and transverse momentum in the range $5\sim20$ GeV[12]? Actually,

$$\sigma(pp\to X(3872)+anything)\cdot BR(X(3872)\to\pi^+\pi^- J/\psi)=5.4\ \text{nb}$$

and

$$\sigma(pp\to\psi(2S)+anything)\cdot BR(\psi(2S)\to\pi^+\pi^- J/\psi)=38\ \text{nb} \quad (16)$$

But, according to Ref. [7]

$$BR(\psi(2S)\to\pi^+\pi^- J/\psi)=0.34 \qquad (17)$$

while

$$0.023<BR(X(3872)\to\pi^+\pi^- J/\psi)<0.066 \qquad (18)$$

according to Ref. [13].

So,

$$0.74<\frac{\sigma(pp\to X(3872)+anything)}{\sigma(pp\to\psi(2S)+anything)}<2.1 \qquad (19)$$

The extended molecule is produced in the hard process as intensively as the compact charmonium. It's a miracle.

As for the problem of the mass shift, Eq. (13), the contribution of the D^-D^{*+} and $\overline{D}^0D^{*0}$ loops, see Fig. 3, into the self energy of the $X(3872)$ resonance, $\Pi_X(s)$, solves it easily.

Let us calculate $I^{D^*\overline{D}}(s)$ in Eq. (8) with the

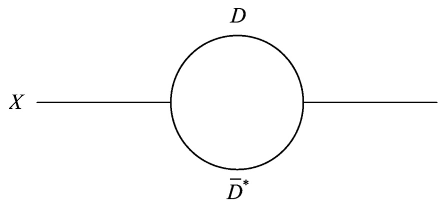


Fig. 3 The contribution of the $\overline{D}^0 D^{*0}$ and $D^- D^{*+}$ loops into the self energy of the $X(3872)$ resonance

help of a cut-off Λ.

$$I^{D^* \overline{D}}(s) = \int_{m_+^2}^{\Lambda^2} \frac{\sqrt{(s' - m_+^2)(s' - m_-^2)}}{s'(s' - s)} \mathrm{d}s' \approx$$

$$2\ln\frac{2\Lambda}{m_+} - 2\sqrt{\frac{m_+^2 - s}{s}} \arctan\sqrt{\frac{s}{m_+^2 - s}} \qquad (20)$$

where $s < m_+^2$, $\Lambda^2 \gg m_+^2$.

The inverse propagator of the $X(3872)$ resonance

$$D_X(s) = m_{\chi_{c1}(2P)}^2 - s - \Pi_X(s) - \iota m_X \Gamma \qquad (21)$$

The renormalization of mass

$$m_{\chi_{c1}(2P)}^2 - m_X^2 - \Pi_X(m_X^2) = 0 \qquad (22)$$

results in

$$\Delta(2m_X + \Delta) = \Pi_X(m_X^2) \approx (g_A^2/8\pi^2) 4\ln(2\Lambda/m_+) \qquad (23)$$

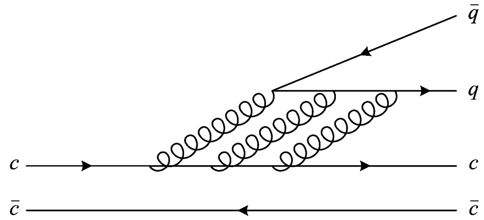
If $\Delta = m_{\chi_{c1}(2P)} - m_X \approx 50$ MeV, then $g_A^2/8\pi \approx 0.2\ \mathrm{GeV}^2$ for $\Lambda = 10$ GeV and $BR(X \to D^0 \overline{D}^{*0} + \overline{D}^0 D^{*0}) \approx 0.3$①.

Thus, we expect that a number of unknown mainly two-gluon decays of $X(3872)$ into non-$D^{*0}\overline{D}^0 + c.c.$ states are considerable②. The discovery of these decays would be a strong (if not decisive) confirmation of our scenario.

As for $BR(X \to \omega J/\psi) \approx BR(X \to \rho J/\psi)$, Eq. (14), this could be a result of dynamics. In our scenario the $\omega J/\psi$ state is produced via the three gluons, see Fig. 4.

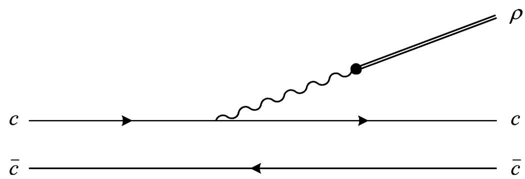
As for the $\rho J/\psi$ state, it is produced both via the one photon, see Fig. 5, and via the three gluons (via the contribution $\approx m_u - m_d$), see Fig. 4.

Close to our scenario is an example of the $J/\psi \to \rho\eta'$ and $J/\psi \to \omega\eta'$ decays. According to Ref. [7]



All possible permutations of gluons are assumed.

Fig. 4 The three-gluon production of the ω and ρ mesons (the ρ meson via the contribution $\approx m_u - m_d$)



All possible permutations of photon are assumed.

Fig. 5 The one-photon production of the ρ meson

$$BR(J/\psi \to \rho\eta') = (1.05 \pm 0.18) \times 10^{-4}$$

and

$$BR(J/\psi \to \omega\eta') = (1.82 \pm 0.21) \times 10^{-4} \qquad (24)$$

Note that in the $X(3872)$ case the ω meson is produced on its tail ($m_X - m_{J/\psi} = 775$ MeV), while the ρ meson is produced on a half.

It is well known that the physics of charmonium ($\bar{c}c$) and bottomonium ($\bar{b}b$) is similar. Let us compare the already known features of $X(3872)$ with the ones of $\Upsilon_{b1}(2P)$.

Recently, the LHCb Collaboration published a landmark result[14]

$$\frac{BR(X \to \gamma\psi(2S))}{BR(X \to \gamma J/\psi)} = C_X \left(\frac{\omega_{\psi(2S)}}{\omega_{J/\psi}}\right)^3 = 2.46 \pm 0.7 \qquad (25)$$

where $\omega_{\psi(2S)}$ and $\omega_{J/\psi}$ are the energies of the photons in the $X \to \gamma\,\psi(2S)$ and $BR(X \to \gamma J/\psi)$ decays, respectively.

On the other hand, it is known[7] that

$$\frac{BR(\chi_{b1}(2P) \to \gamma\Upsilon(2S))}{BR(\chi_{b1}(2P) \to \gamma\Upsilon(1S))} = C_{\chi_{b1}(2P)} \left(\frac{\omega_{\Upsilon(2S)}}{\omega_{\Upsilon(1S)}}\right)^3 = 2.16 \pm 0.28 \qquad (26)$$

① The assumption of the determining role of the $D^* \overline{D} + c.c.$ channels in the shift of the mass of the $\chi_{c1}(2P)$ meson is based on the following reasoning. Let us imagine that D and D^* mesons are light, for example, like the K and K^* mesons. Then the width of X (3872) meson is equal 50 MeV for $g_A^2/8\pi = 0.2\ \mathrm{GeV}^2$, which is much more than the width of its decay into all non-($D^{*0}\overline{D}^0$ + c. c.) channels, $\Gamma < 1.2$ MeV. That is, to our case the coupling of the $X(3872)$ meson with the $D^* \overline{D} + c.c.$ channels is rather strong.

② Note that in the $\chi_{c1}(1P)$ case the width of the two-gluon decays equals 0.56 MeV[7], which agrees with $\Gamma < 1.2$ MeV satisfactory.

where $\omega_{\Upsilon(2S)}$ and $\omega_{\Upsilon(1S)}$ are the energies of the photons in the $\chi_{b1}(2P)\to\gamma\Upsilon(2S)$ and $\chi_{b1}(2P)\to\gamma\Upsilon(1S)$ decays, respectively.

Consequently,

$$C_X = 136.78 \pm 38.89 \tag{27}$$

and

$$C_{\chi_{b1}(2P)} = 80.00 \pm 10.37 \tag{28}$$

as all most lucky versions of the potential model predicted for the quarkonia $C_{\chi_{c1}(2P)} \gg 1$ and $C_{\chi_{b1}(2P)} \gg 1$.

According to Ref. [7]

$$BR(\chi_{b1}(2P)\to\omega\Upsilon(1S)) = (1.63 \pm^{0.4}_{0.34})\% \tag{29}$$

If the one-photon mechanism dominates in the $X(3872)\to\rho J/\psi$ decay, see Fig. 5, then one should expect

$$BR(\chi_{b1}(2P)\to\rho\Upsilon(1S)) \approx (e_b/e_c)^2 \times 1.6\% = (1/4)\times 1.6\% = 0.4\% \tag{30}$$

where e_c and e_b are the charges of the c and b quarks, respectively.

If the three-gluon mechanism (its part $\approx m_u - m_d$) dominates in the $X(3872)\to\rho J/\psi$ decay, see Fig. 4, then one should expect

$$BR(\chi_{b1}(2P)\to\rho\Upsilon(1S)) \approx 1.6\% \tag{31}$$

3 Conclusion

We believe that the discovery of a significant number of unknown decays of the $X(3872)$ into non-$D^{*0}\overline{D}^0 + c.c.$ states via two gluons and discovery of the $\chi_{b1}(2P)\to\rho\Upsilon(1S)$ decay could decide the destiny of X(3872).

Once more, we discuss the scenario where the $\chi_{c1}(2P)$ charmonium sits on the $D^{*0}\overline{D}^0$ threshold but not a mixing of the giant $D^*\overline{D}$ molecule and the compact $\chi_{c1}(2P)$ charmonium, see, for example, Refs. [15-16] and references cited therein. Note that the mixing of such states requests special justification. That is, it is necessary to show that the transition of the giant molecule into the compact charmonium is considerable at insignificant overlapping of their wave functions. Such a transition $\approx\sqrt{V_{\chi_{c1}(2P)}/V_{X(3872)}}$ and a branching ratio of a decay via such a transition $\approx V_{\chi_{c1}(2P)}/V_{X(3872)}$.

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