Novel charmonium-like structures in the $J/\psi\phi$ and $J/\psi\omega$ invariant mass spectra

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Stimulated by the new evidence of $Y^\prime(4274)$ observed in the $J/\psi\phi$ invariant mass spectrum, we first propose the charmonium-like state $Y^\prime(4274)$ as the $S$-wave $D_s^*D_{s0}(2317) + h.c.$ molecular state with $J^P = 0^-$, which is supported well by dynamics study of the system composed of the pseudoscalar and scalar charmed mesons. The $S$-wave $D^0D_s(2400) + h.c.$ molecular charmonium appears as the molecular partner of $Y^\prime(4274)$, which is in accord with the enhancement structure appearing at 4.2 GeV in the $J/\psi\omega$ invariant mass spectrum from $B$ decays. Our study shows that the enhancement structures, i.e., the newly observed $Y^\prime(4274)$ and the previously announced $Y(4140)/Y(3930)$ in the $J/\psi\phi$ and $J/\psi\omega$ invariant mass spectra, can be understood well under the uniform framework of the molecular charmonium, which can be tested by future experiments.

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Very recently the CDF Collaboration $[1]$ studied the $J/\psi\phi$ invariant mass spectrum in the $B \to J/\psi\phi K$ channel based on the sample of $p\bar{p}$ collision data with an integrated luminosity of 6 fb$^{-1}$. Besides confirming the previous $Y(4140)$ state $[2]$, CDF also reported the observation of an explicit enhancement structure with 3.1$\sigma$ significance in the $J/\psi\phi$ invariant mass spectrum, which is of mass $M = 4274.4^{+0.8}_{-0.4}(\text{stat})$ MeV and width $\Gamma = 32.3^{+15.9}_{-9.5}(\text{stat})$ MeV $[1]$. We will refer to this new structure by the name $Y(4274)$ in this letter.

The appearance of $Y(4274)$ in the $J/\psi\phi$ invariant mass spectrum not only makes the charmonium-like family abundant, but also raises our interest in exploring the origin of enhancement structures in the $J/\psi\phi$ invariant mass spectrum and revealing the relation between $Y(4274)$ and $Y(4140)$, which will be helpful to improve our knowledge of the underlying properties of charmonium-like state.

The previous observation of $Y(4140)$ has stimulated great interest among theorists, especially when associating it with $Y(3930)$ reported by the Belle Collaboration $[3]$ and confirmed by the BaBar Collaboration $[4]$. Both $Y(4140)$ and $Y(3930)$ were observed in the mass spectrum of $J/\psi + light \text{ vector meson}$ in $B$ meson decay

$$B \to K + \begin{cases} J/\psi\phi \implies Y(4140) \\ J/\psi\omega \implies Y(3930) \end{cases}$$

Generally in the weak decays of $B$ meson, the $c\bar{c}$ pair creation mainly results from the color-octet mechanism. Furthermore, a color-octet $q\bar{q}$ pair is easily popped out by a gluon.

Thus, $c$ and $\bar{c}$ capture $q$ and $\bar{q}$ respectively to form a pair of charmed mesons. By this mechanism, a pair of the charm-strange mesons with the low momentum easily interact with each other and even form the molecular charmonium. Additionally, $Y(4140)$ and $Y(3930)$ are close to the thresholds of $D^*_sD^*_s$ and $D^*D^*$ respectively, and satisfy an almost exact mass relation

$$M_{Y(4140)} - 2M_{D^*_s} \approx M_{Y(3930)} - 2M_{D^*}.$$  \hspace{1cm} (1)

The mass difference $m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ distribution (histogram) for events in the $B^+$ mass window $[1]$. Besides $Y(4140)$, one explicit enhancement appears around 4274 MeV. Here, the purple dashed line is the background from the three-body phase space. The blue solid line is the fitting result with resonance parameters of $Y(4140)$ and $Y(4274)$ resonances in Ref. $[1]$. The vertical red dashed lines denote the thresholds of $D^*_sD^*_s$, $D_sD_{s0}(2317)$, $D_sD_{s1}(2460)$, $D^*_sD_{s0}(2317)$, $D_sD_{s1}(2536)$, $D_sD_{s2}(2573)$, $D^*_sD_{s1}(2460)$ and $D^*_sD_{s1}(2536)$.

FIG. 1: (Color online.) The mass difference $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ distribution (histogram) for events in the $B^+$ mass window $[1]$. Besides $Y(4140)$, one explicit enhancement appears around 4274 MeV. Here, the purple dashed line is the background from the three-body phase space. The blue solid line is the fitting result with resonance parameters of $Y(4140)$ and $Y(4274)$ resonances in Ref. $[1]$. The vertical red dashed lines denote the thresholds of $D^*_sD^*_s$, $D_sD_{s0}(2317)$, $D_sD_{s1}(2460)$, $D^*_sD_{s0}(2317)$, $D_sD_{s1}(2536)$, $D_sD_{s2}(2573)$, $D^*_sD_{s1}(2460)$ and $D^*_sD_{s1}(2536)$.
$M_{Y(3930)} \sim M_\rho - M_\omega$. The peculiarity of $B \to K(c\bar{c})$ and the similarity between $Y(4140)$ and $Y(3930)$ provoke an uniform molecular charmonium picture to reveal the underlying structure of $Y(4140)$ and $Y(3930)$ [5,6]. Applying $D_1^* D_1^*$ and $D_1^* D_1^*$ molecular structures to explain $Y(4140)$ and $Y(3930)$ respectively not only solves a long-standing puzzle of the structure of $Y(3930)$, but also opens a window to investigate the hadron dynamics of exotic state beyond the conventional $q \bar{q}$ and $qgq$ states. A series of research work related with $Y(4140)$ were carried out later [5–19].

In Fig. [1] we present the comparison between the experimental data [11] and the thresholds of the charmed-strange meson pairs. $Y(4274)$ is just below the threshold of $D_s \bar{D}_s(2317)$ similar to the situation of $Y(4140)$, which stimulates us to deduce naturally that $Y(4274)$ enhancement results from an S-wave $D_s \bar{D}_s(2317) + h.c.$ molecular system $Y^{ss}$ with the flavor wave function

$$|Y^{ss}\rangle = \frac{1}{\sqrt{2}} \left[ |D_s^+ D_s^-\rangle + |D_s^- D_s^+\rangle \right].$$  \hspace{1cm} (2)

The $C$ parity of the isoscalar $Y(4274)$ is positive due to the $Y(4274) \to J/\psi \phi$ decay mode observed by CDF. As the cousin of $Y^{ss}$, $Y^{u\bar{u}/d\bar{d}}$ is of the flavor wave function

$$|Y^{u\bar{u}/d\bar{d}}\rangle = \frac{1}{2} \left[ |D_s^0 D_s^0\rangle + |D_s^0 D_s^+\rangle + |D_s^- D_s^-\rangle \right].$$  \hspace{1cm} (3)

For such S-wave pseudoscalar-scalar systems, their quantum number must be $J^P = 0^-$. Performing dynamical investigations of $Y^{ss}$ and $Y^{u\bar{u}/d\bar{d}}$ can answer whether there exist $Y^{ss}$ and $Y^{u\bar{u}/d\bar{d}}$ molecular systems, which is one of the main tasks of this letter. What is more important is that understanding the underlying structure of $Y(4274)$ will be helpful for revealing the properties of $Y(4140)$ [5,6] taking into account the similarities between $Y(4274)$ and $Y(4140)$.

Using the effective Lagrangian in the heavy meson chiral perturbation theory (HMChPT) [20,21] and the method developed in literature [22], we obtain the effective potentials of $Y^{ss}$ and $Y^{u\bar{u}/d\bar{d}}$ states [23]

$$V^{ss}_{eff}(r) = V_{\rho}^{Direct}(r) + \frac{1}{3} V_{\sigma}^{Cross}(r),$$  \hspace{1cm} (4)

$$V^{u\bar{u}/d\bar{d}}_{eff}(r) = \frac{3}{2} V_{\rho}^{Direct}(r) + \frac{1}{2} V_{\omega}^{Direct}(r) + V_{\sigma}^{Direct}(r) + \frac{3}{2} V_{\pi}^{Cross}(r) + \frac{1}{6} V_{\eta}^{Cross}(r).$$  \hspace{1cm} (5)

Here, the subscript of the sub-potential denotes the exchanged light meson. The general expressions of the sub-potentials corresponding to the pseudoscalar, sigma and vector meson exchanges are

$$V_{\rho}^{Direct}(r) = \frac{g_\rho^2}{2} Y(\Lambda, q_0 = 0, m_\rho, r),$$  \hspace{1cm} (6)

$$V_{\omega}^{Direct}(r) = g_{\omega} g_{\rho} Y(\Lambda, q_0 = 0, m_\omega, r),$$  \hspace{1cm} (7)

$$V_{\pi}^{Cross}(r) = \frac{g_{\pi}^2}{f_\pi^2} Y(\Lambda, q'_0, m_\pi, r),$$  \hspace{1cm} (8)

where $f_\pi = 132$ MeV and $g_\rho = m_\rho/f_\pi = 5.8$, $g_\omega$, $h$, $b^{\rho\sigma}$, $b^{\sigma\pi}$ are the parameters in the effective light mesons with the light mesons [21]. $q'_0$ is taken as $m_D - m_D$, and $m_D - m_D$ for $Y^{ss}$ and $Y^{u\bar{u}/d\bar{d}}$, respectively. And the $Y$ function is

$$Y(\Lambda, \kappa, m, r) = \begin{cases} \frac{1}{4\epsilon} \left( e^{-\epsilon r} - e^{-\epsilon r'} \right) + \frac{1}{8\epsilon} \left( e^{-\epsilon r} - e^{-\epsilon r'} \right) \frac{r}{r'}, & \text{if } |\kappa| \leq m, \\ \frac{1}{4\epsilon} \left( \cos(\xi r' - \epsilon r') - \cos(\xi r' - \epsilon r') \right) + \frac{1}{8\epsilon} \left( \cos(\xi r' - \epsilon r') - \cos(\xi r' - \epsilon r') \right), & \text{otherwise}. \end{cases}$$

with $\xi = \sqrt{m^2 - \Lambda^2}$, $\xi' = \sqrt{m^2 - \Lambda^2}$ and $\Lambda$ is the cutoff to cure the singularity of the effective potential.

In Fig. 2 one presents the line shapes of the potentials listed in Eqs. (4) and (5). For $Y^{ss}$, the exchange potential of the $\phi$ meson can be ignored compared with that of the $\eta$ meson. The total effective potential of $Y^{ss}$ is dominated by the $\eta$ exchange potential. For $Y^{u\bar{u}/d\bar{d}}$, the $\pi$ meson plays an important role especially in the range of $r > 5$ GeV$^{-1}$ since the exchange potentials of $\rho$, $\omega$, $\sigma$ and $\eta$ decay exponentially with $r$. The behavior of the potential depicted in Fig. 2 indicates that we only need to consider the $\eta$ meson exchange potential for $Y^{ss}$ and the $\pi$ meson exchange potential for $Y^{u\bar{u}/d\bar{d}}$ when finding the bound state solution by solving Schrödinger equation. Furthermore, whether there exist bound state solutions for $Y^{ss}$ and $Y^{u\bar{u}/d\bar{d}}$ systems is closely related to the corresponding strengths of the $D_s(2317)\bar{D}_s$, $\eta$ and $D_0(2400)\eta$ couplings.

In Fig. 2 we show the variation of the numerical result of the bound state solutions for $Y^{ss}$ with the values of $h$ and $\Lambda$, which indicates that there indeed exists a $D_s(2317)\bar{D}_s + h.c.$ molecular charmonium corresponding to newly observed enhancement $Y(4274)$. Our numerical results overlap with the mass difference ($\sim -11$ MeV) between $Y(4274)$ and the threshold of $D_s(2317)\bar{D}_s$. The corresponding cutoff $\Lambda$ lies in a reasonable range which is expected to be around 1-3 GeV.
We also find that the larger $|h|$ values make the corresponding $\Lambda$ become smaller, i.e., $\Lambda$ tends to be around 1 GeV, which is fully consistent with the expected behavior of the potential of the S-wave $D_{0}(2317)\bar{D}_{s} + h.c.$ system.

Besides supporting the assignment of $Y(4274)$ as the S-wave $D_{0}(2317)\bar{D}_{s} + h.c.$ molecular state, our dynamical calculation also provides a novel approach to extract the $h$ parameter, which encodes the important information of the $D_{0}(2317)\bar{D}_{s}$ interaction and the underlying properties of $D_{0}(2317)$ \cite{24}. This coupling can not be extracted experimentally since the $D_{0}(2317) \rightarrow D_{s}\eta$ decay is forbidden kinematically. Our result indicates that the $|h|$ value corresponding to the binding energy of the S-wave $D_{0}(2317)\bar{D}_{s} + h.c.$ system consistent with mass difference ($\sim -11$ MeV) is in the range $1.2 \sim 1.5$ associated with reasonable $\Lambda$ value, which can be confirmed by further theoretical study.

We extend the same formalism to the $Y^{uud/\bar{d}d}$ system, where input parameter $h$ for the $D_{0}(2400)\bar{D}\pi$ coupling is constrained by the decay width of the $D_{0}(2400) \rightarrow D\pi$ to be $h = -0.56 \pm 0.2$ \cite{21}. The binding energy of the $Y^{uud/\bar{d}d}$ system is $-9.85, -10.11, -10.23, -10.30, -10.34, -10.38, -10.42$ MeV corresponding to the typical value of $\Lambda = 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5$ GeV, where the bound state solution of the $Y^{uud/\bar{d}d}$ system is insensitive to $\Lambda$, which indicates the existence of the molecular cousin of the S-wave $D_{0}(2317)\bar{D}_{s} + h.c.$ molecular state, i.e., an S-wave $D_{0}(2400)\bar{D} + h.c.$ molecular charmonium. Thus, finding the evidence of S-wave $D_{0}(2400)\bar{D} + h.c.$ molecular charmonium can provide important support for the assignment of $Y(4274)$ as an S-wave $D_{0}(2317)\bar{D}_{s} + h.c.$ molecular state. The important hidden-charm decay mode of the S-wave $D_{0}(2400)\bar{D} + h.c.$ molecular charmonium is $J/\psi\omega$, which is the same as in the case of $Y(3930)$ \cite{3,4}.

From the published experimental data of the $J/\psi\omega$ invariant mass spectrum \cite{3,4}, we indeed notice an enhancement structure around 4.2 GeV just below the threshold of the $D_{0}(2400)\bar{D}$ pair as illustrated in Fig. 4, which is amazingly consistent with our prediction of the S-wave $D_{0}(2400)\bar{D} + h.c.$ molecular charmonium. We expect further high-statistics measurement from future experiments to test our prediction of the S-wave $D_{0}(2400)\bar{D} + h.c.$ molecular charmonium.

The S-wave $D_{0}(2317)\bar{D}_{s}/D_{0}(2400)\bar{D}$ molecular state with spin-parity $J^{P} = 0^{-}$ does not couple to the $D\bar{D}/D_{s}\bar{D}_{s}$ channels, which is strictly forbidden by the conservation of the parity and angular momentum. In addition, the S-wave $D_{0}(2317)\bar{D}_{s}/D_{0}(2400)\bar{D}$ molecular state may couple to the $D'\bar{D}/D'_{s}\bar{D}_{s}$ and $D'\bar{D'}/D'_{s}\bar{D}'_{s}$ via P-wave, which is expected to be suppressed compared to the S-wave mode. Due to the above reasons, the coupled-channel effect on the S-wave $D_{0}(2317)\bar{D}_{s}/D_{0}(2400)\bar{D}$ molecular state may be weak, which is ignored in this work.

As an S-wave $D_{0}(2317)\bar{D}_{s} + h.c.$ molecular charmonium with $J^{P} = 0^{-}$, the decay modes of $Y(4274)$ include the hidden-charm decay mode $J/\psi\phi$ observed by CDF \cite{1}, the two-body P-wave open-charm decays $D_{s}\bar{D}_{s} + h.c.$ and $D'_{s}\bar{D}'_{s}$, the radiative decay $D_{s}\bar{D}_{s}\gamma + h.c.$, and the iso-spin violating three-body strong decay $D_{s}\bar{D}_{s}\eta^{0}$ via the $\eta - \eta^{0}$ mixing mechanism \cite{2,3}. Similarly $Y^{uud/\bar{d}d}$ can decay into $J/\psi\omega$, $D\bar{D} + h.c.$, $D'\bar{D'} + h.c.$, $D\bar{D}\pi + h.c.$ etc.

After figuring out the underlying structure of $Y(4274)$ and predicting its molecular cousin, we notice that there exist two event clusters around the ranges of $\Delta M \sim 1.27$ GeV and $1.4 < \Delta M < 1.5$ GeV marked by yellow and pink in Fig. 11 if we focus on the remaining CDF’s data corresponding to $\Delta M > 1.24$ GeV. If these two event clusters are confirmed by future experiments, we might also try to understand them under the same framework of the molecular charmonium. Basing on the present low-statistic data \cite{1}, we speculate that the structure appearing at $\Delta M \sim 1.27$ is related to the $D_{s}\bar{D}_{s}(2460)$ or $D'_{s}\bar{D}_{s}(2317)$ system. The other one in the range $1.4 < \Delta M < 1.5$ GeV may result from the $D_{s}\bar{D}_{s}(2536)$, $D_{s}\bar{D}_{s}(2573)$, $D'_{s}\bar{D}_{s}(2460)$ and $D'_{s}\bar{D}_{s}(2536)$ systems since the event cluster in the range $1.4 < \Delta M < 1.5$ GeV just overlaps with the corresponding thresholds (see Fig. 1 for more details). One may recall the similar situation before finding...
the evidence of $Y(4274)$ by CDF \cite{1}. The CDF’s data with an integrated luminosity of $2.7 \text{ fb}^{-1}$ reported in Ref. \cite{4} only displayed the event cluster at $4.27 \text{ GeV}$ besides the evidence of $Y(4140)$. Confirming the above speculation by further experimental study of $J/\psi\phi$ invariant mass spectrum from $B$ decay will not only test the molecular charmonium assignments of $Y(4140)$ and $Y(4274)$, but also improve our understanding of the line shapes appearing at hidden-charm invariant mass spectra.

In summary, the newly observed structure $Y(4274)$ in the $J/\psi\phi$ invariant mass spectrum is first interpreted as the S-wave $D_s^- D_{s0} (2317) + h.c.$ molecular charmonium well from the dynamical study of the system composed of the pseudoscalar and scalar charmed mesons. Furthermore, we predict the S-wave $D D_s (2400) + h.c.$ molecular charmonium appearing as the cousin of $Y(4274)$, which is consistent with the enhancement structure around $4.2 \text{ GeV}$ in the $J/\psi\omega$ invariant mass spectrum from $B$ decay \cite{3}. Thus, the enhancement structures including the present $Y(4274)$, the previous $Y(4140)$ and $Y(3930)$ observed in the $J/\psi\phi$ \cite{2} and $J/\psi\omega$ \cite{3} invariant mass spectra respectively, can be accommodated well in the uniform framework of the molecular charmonium. In addition, we find two possible event clusters in the $J/\psi\phi$ invariant mass spectrum might related to the molecular charmonia, which can be tested by high-statistic experimental data in future experiment.

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[1] K. Yi [CDF Collaboration], [arXiv:1010.3470 [hep-ex]].
[2] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 102, 242002 (2009) [arXiv:0903.2229 [hep-ex]].
[3] K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 94, 182002 (2005) [arXiv:hep-ex/0408126].
[4] B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 101, 082001 (2008) [arXiv:0711.2047 [hep-ex]].
[5] X. Liu and S. L. Zhu, Phys. Rev. D 80, 017502 (2009) [arXiv:0903.2529 [hep-ph]].
[6] X. Liu, Z. G. Luo, Y. R. Liu and S. L. Zhu, Eur. Phys. J. C 61, 411-428 (2009) [arXiv:0808.0073 [hep-ph]].
[7] N. Mahajan, Phys. Lett. B 679, 228 (2009) [arXiv:0903.3107 [hep-ph]].
[8] Z. G. Wang, Eur. Phys. J. C 63, 115 (2009) [arXiv:0903.5200 [hep-ph]].
[9] T. Branz, T. Gutsche and V. E. Lyubovitskij, Phys. Rev. D 80, 054019 (2009) [arXiv:0903.5424 [hep-ph]].
[10] R. M. Albuquerque, M. E. Bracco and M. Nielsen, Phys. Lett. B 678, 186 (2009) [arXiv:0903.5540 [hep-ph]].
[11] X. Liu, Phys. Lett. B 680, 137 (2009) [arXiv:0904.0136 [hep-ph]].
[12] G. J. Ding, Eur. Phys. J. C 64, 297 (2009) [arXiv:0904.1782 [hep-ph]].
[13] J. R. Zhang and M. Q. Huang, J. Phys. G 37, 025005 (2010) [arXiv:0905.4178 [hep-ph]].
[14] E. van Beveren and G. Rupp, [arXiv:0906.2278 [hep-ph]].
[15] F. Stancu, [arXiv:0906.2485 [hep-ph]].
[16] X. Liu and H. W. Ke, Phys. Rev. D 80, 034009 (2009) [arXiv:0907.1349 [hep-ph]].
[17] Z. G. Wang, Z. C. Liu and X. H. Zhang, Eur. Phys. J. C 64, 373 (2009) [arXiv:0907.3467 [hep-ph]].
[18] N. V. Drenska, R. Faccini and A. D. Polosa, Phys. Rev. D 79, 077502 (2009) [arXiv:0902.2803 [hep-ph]].
[19] R. Molina and E. Oset, Phys. Rev. D 80, 114013 (2009) [arXiv:0907.3043 [hep-ph]].
[20] T. M. Yan, H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin and H. L. Yu, Phys. Rev. D 46, 1148 (1992) [Erratum-ibid. D 55, 5851 (1997)].
[21] R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio and G. Nardulli, Phys. Rept. 281, 145 (1997) [arXiv:hep-ph/9605342].
[22] W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D 68, 054024 (2003) [arXiv:hep-ph/0305049].
[23] X. Liu, Y. R. Liu, W. Z. Deng and S. L. Zhu, Phys. Rev. D 77, 034003 (2008) [arXiv:0711.0494 [hep-ph]]; Y. R. Liu, X. Liu, W. Z. Deng and S. L. Zhu, Eur. Phys. J. C 56, 63 (2008) [arXiv:0801.3540 [hep-ph]]; X. Liu, Y. R. Liu, W. Z. Deng and S. L. Zhu, Phys. Rev. D 77, 094015 (2008) [arXiv:0803.1295 [hep-ph]].
[24] L. L. Shen, X. L. Chen, Z. G. Luo, P. Z. Huang, S. L. Zhu, P. F. Yu and X. Liu, accepted by Eur. Phys. J. C, arXiv:1005.0994 [hep-ph].
[25] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 90, 242001 (2003) [arXiv:hep-ex/0304021].