$Y(4143)$ is probably a molecular partner of $Y(3930)$

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After discussing the various possible interpretations of the $Y(4143)$ signal observed by the CDF collaboration in the $J/\psi\phi$ mode, we tend to conclude that $Y(4143)$ is probably a $D_s^*\bar{D}_s^*$ molecular state with $J^{PC}=0^{++}$ or 2^{++} while $Y(3930)$ is its $D^*\bar{D}^*$ molecular partner as predicted in our previous work [1]. Both the hidden-charm and open charm two-body decays occur through the rescattering of the vector components within the molecular states while the three- and four-body open charm decay modes are forbidden kinematically. Hence their widths are narrow naturally. CDF, Babar and Belle collaborations may have discovered heavy molecular states already. We urge experimentalists to measure their quantum numbers and explore their radiative decay modes in the future.

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I. INTRODUCTION

The charmonium system has been a rich gold mine, which continues to deepen our knowledge of strong interaction. Especially starting from 2003 many new charmonium or charmonium-like states were discovered experimentally, some of which do not easily fit into the conventional quark model picture. Let's list these new states: $X(3872)$, $X(3940)/Y(3930)/Z(3930)$, $Y(4260)$, $Z(4430)$ etc. There have been many surprises and unexpected in this active field. The most recent one came from the CDF Collaboration [2].

In the exclusive $B^+\to J/\psi\phi K^+$ decays, the CDF collaboration observed a narrow structure $Y(4143)$ near the $J/\psi\phi$ threshold ($m_{J/\psi}+m_\phi=4.117$ GeV) with a statistical significance of 3.8σ. The mass and width of this signal are measured to be $4143\pm2.9\pm1.2$ MeV and $11.7^{+8.3}_{-5.0}\pm3.7$ MeV [2]. For comparison, $Y(4143)$ is very similar to the charmonium-like state $Y(3930)$ which was observed by both Belle and Babar collaborations near the $J/\psi\omega$ threshold ($m_{J/\psi}+m_\omega=3.88$ GeV) [3, 4]. The mass and width of Y(3930) are $3914.6^{+3.8}_{-3.4}\pm2.0$ MeV and $34^{+12}_{-8}\pm5$ MeV [4].

Clearly the C-parity and G-parity of $Y(4143)$ are even. Around this mass region, $Y(4143)$ may naively be speculated to be an excited charmonium state. We list some possibilities below:

1. the second radial excitation of the P-wave charmonium: χ''_{cJ}

   Sometimes either $X(3872)$ or $X(3930)$ is speculated to be χ'_{c1}. Then $Y(4143)$ seems plausible as a candidate of χ''_{cJ}.

2. $\eta_c(3S)$

   As $\eta_c(3S)$, its mass seems too high compared with $\psi(3S)$ at 4040 MeV.

3. Other higher lying states such as $2^1D_2, 1^3F_{2,3,4}$ etc.

However as emphasized by CDF collaboration [2], $Y(4143)$ lies well above the open charm decay threshold. Charmoniums with this mass would decay into an open charm pair dominantly. The branching fraction of its hidden charm decay mode $J/\psi\phi$ is expected to be tiny. Thus, both the narrow width of $Y(4143)$ and its large hidden charm decay pattern disfavor the conventional charmonium interpretation.

One may be tempted to try the non-conventional assignment of $Y(4143)$ as a tetraquark state. In fact, the $J^P=0^+,1^+$ $c\bar{c}s\bar{s}$ tetraquark states were predicted to be around 4.1 GeV in the simple chromo-magnetic interaction

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quark model while their $J^P = 2^+$ partner seems unbound [5]. However tetraquarks will fall apart into a pair of charmed mesons very easily. As a tetraquark, the width of $Y(4143)$ would be around several hundred MeV instead of 12 MeV as observed by CDF.

The B meson decay process does not provide a glue-rich environment as in the Upsilon/charmonium annihilation. So the possibility of $Y(4143)$ being a glueball is small.

Recall that $Y(4260)$ is proposed as the 1^{--} hybrid charmonium state [6, 7, 8]. All current experimental information is compatible with this assumption [9]. The only slightly worrisome issue is the leptonic width $\Gamma[Y(4260)\to e^+e^-]\approx 0.8$ keV if one assumes $B[Y(4260)\to J/\psi\pi^+\pi^-]\approx 1\%$. Such a leptonic width naively seems a little large for a vector hybrid. Fortunately no dynamical selection rule has been discovered to suppress the leptonic width of a hybrid state up to now.

Within this context, $Y(4143)$ could be an exotic charmonium with $J^P = 1^{-+}$, which is a partner of $Y(4260)$ within the same $J^P = 1^-$ hybrid charmonium family. One may challenge this assignment with the following three facts: (1) the narrow width of $Y(4143)$ which is much smaller than that of $Y(4260)$; (2) the different decay patterns of $Y(4143)$ and $Y(4260)$. $Y(4260)$ is observed in $J/\psi\pi^+\pi^-$, $J/\psi K^+K^-$ modes while $Y(4143)$ only in $J/\psi\phi$; (3) the similarity between $Y(4143)$ and $Y(3930)$. One does not expect two exotic 1^{-+} states lying so closely.

In fact, the extreme similarity between $Y(4143)$ and $Y(3930)$ suggests that they be partner molecular states belonging to the same representation as predicted in our previous work [1], where we have performed a systematic study of the possible molecular states composed of a pair of heavy mesons in the framework of the meson exchange model. $Y(4143)$ is a $D_s^*\bar{D}_s^*$ molecular state while $Y(3930)$ is its $D^*\bar{D}^*$ molecular partner. Their hidden charm decays occur through the rescattering mechanism [10]. We present more details in Sections II-III.

II. $Y(4143)$ AND $Y(3930)$ AS HEAVY MOLECULAR CANDIDATES

Since $Y(4143)$ and $Y(3930)$ were observed in the $J/\psi\phi$ and $J/\psi\omega$ modes, these two states are isoscalars. The isoscalar heavy molecular states in the vector-vector channel are denoted as Φ_8^{**0} and Φ_{s1}^{**0} respectively in our previous work [1]. From now on we identify Φ_8^{**0} as $Y(3930)$ and Φ_{s1}^{**0} as $Y(4143)$. Their flavor wave functions are

$$\begin{aligned}|Y(3930)\rangle &= \frac{1}{\sqrt{2}}[|D^{*0}\bar{D}^{*0}\rangle + |D^{*+}D^{*-}\rangle],\\ |Y(4143)\rangle &= |D_s^{*+}D_s^{*-}\rangle.\end{aligned}$$

We used the following effective Lagrangians to derive the meson exchange potentials of $Y(4143)$ and $Y(3930)$:

$$\begin{aligned}\mathcal{L}_{\mathcal{D}^*\mathcal{D}^*\mathbb{P}} &= \frac{1}{2}g_{\mathcal{D}^*\mathcal{D}^*\mathbb{P}}\varepsilon_{\mu\nu\alpha\beta}\left(D_a^{*\mu}\partial^\alpha\mathcal{D}_b^{*\beta\dagger} - \mathcal{D}_b^{*\beta\dagger}\partial^\alpha\mathcal{D}_a^{*\mu}\right)\partial^\nu\mathbb{P}_{ab},\\ \mathcal{L}_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}} &= ig_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}\left(\mathcal{D}_a^{*\nu\dagger}\partial^\mu\mathcal{D}_{\nu,b}^* - \mathcal{D}_{\nu b}^*\partial^\mu\mathcal{D}_a^{*\nu\dagger}\right)(\mathbb{V}_\mu)_{ab} + 4if_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}D_{\mu a}^{*\dagger}D_{\nu b}^*(\partial^\mu\mathbb{V}^\nu - \partial^\nu\mathbb{V}^\mu)_{ab},\\ \mathcal{L}_{\mathcal{D}^*\mathcal{D}^*\sigma} &= 2\,m_{\mathcal{D}^*}\,g_\sigma\mathcal{D}_a^{*\alpha}\mathcal{D}_{\alpha a}^{*\dagger}\sigma,,\end{aligned}$$

where $\mathcal{D}^{(*)}$=$((\bar{D}^0)^{(*)},\ (D^-)^{(*)},\ (D_s^-)^{(*)})$. $\mathbb{P}$ and $\mathbb{V}$ are the octet pseudoscalar and nonet vector meson matrices respectively.

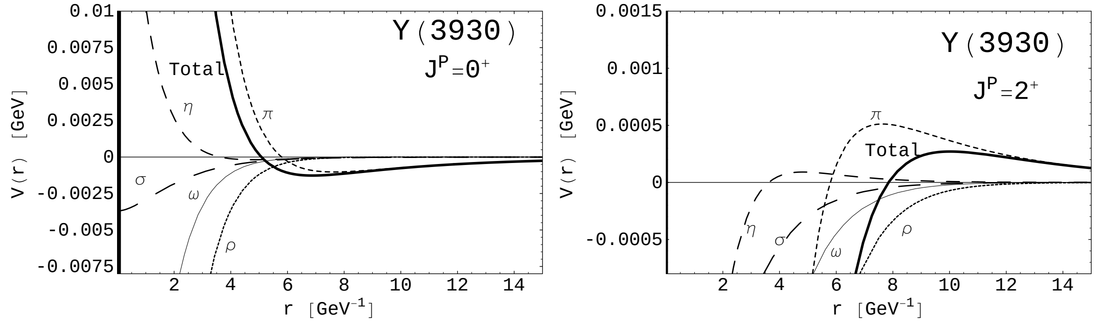
In general, the possible quantum numbers of the S-wave vector-vector system are $J^P = 0^+, 1^+, 2^+$. However for the neutral $D^*\bar{D}^*$ system with $C = +1$, we can have $J^P = 0^+$ and 2^+ only since $C = (-)^{L+S}$ and $J = S$ with $L = 0$. The exchanged mesons include the pseudoscalar, vector and σ mesons. Details of the derivation of the exchange potential can be found in Ref. [1]. We collect the resulting expressions below:

$$\begin{aligned}\mathcal{V}(r)_{Y(4143)}^{[J]} &= \frac{1}{6}g^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{P}}\,\mathcal{A}[J]Z[\Lambda, m_\eta, r] - \left[\frac{g^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}}{4m^2_{\mathcal{D}_s^*}m^2_\phi}\,\mathcal{C}[J]\,X[\Lambda, m_\phi, r]\right.\\ &\quad\left. + g^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}\,\mathcal{C}[J]\,Y[\Lambda, m_\phi, r] + \frac{4f^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}}{m^2_{\mathcal{D}_s^*}}\,\mathcal{B}[J]\,Z[\Lambda, m_\phi, r]\right], \qquad (1)\end{aligned}$$

$$
\begin{aligned}
\mathcal{V}(r)^{[J]}_{Y(3930)} = {} & g^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{P}}\,\mathcal{A}[J]\left[\frac{3}{8}Z[\Lambda,m_\pi,r]+\frac{Z[\Lambda,m_\eta,r]}{24}\right]-g^2_\sigma\,\mathcal{C}[J]\,Y[\Lambda,m_\sigma,r] \\
& -\frac{3}{2}\left[\frac{g^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}}{4m^2_{\mathcal{D}^*}m^2_\rho}\,\mathcal{C}[J]\,X[\Lambda,m_\rho,r]+g^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}\,\mathcal{C}[J]\,Y[\Lambda,m_\rho,r]+\frac{4f^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}}{m^2_{\mathcal{D}^*}}\,\mathcal{B}[J]\,Z[\Lambda,m_\rho,r]\right] \\
& -\frac{1}{2}\left[\frac{g^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}}{4m^2_{\mathcal{D}^*}m^2_\omega}\,\mathcal{C}[J]\,X[\Lambda,m_\omega,r]+g^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}\,\mathcal{C}[J]\,Y[\Lambda,m_\omega,r]+\frac{4f^2_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}}}{m^2_{\mathcal{D}^*}}\,\mathcal{B}[J]\,Z[\Lambda,m_\omega,r]\right]
\end{aligned}
\tag{2}
$$

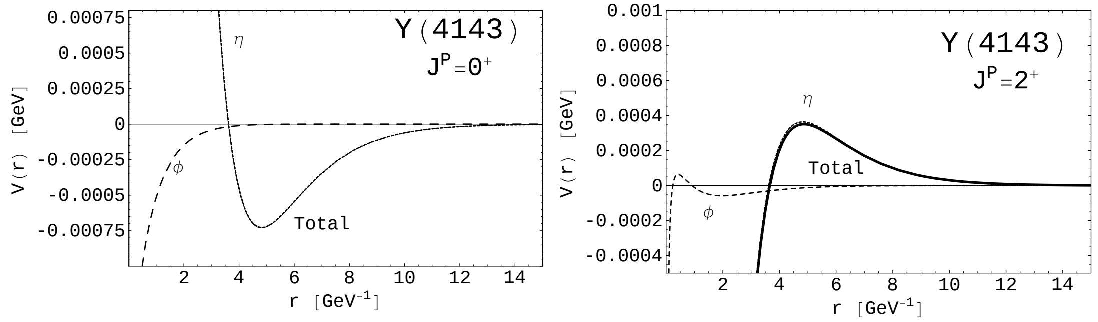
with $Y[\Lambda,m,r] = \frac{1}{4\pi r}\left(e^{-mr}-e^{-\Lambda r}\right) - \frac{\xi^2}{8\pi\Lambda}e^{-\Lambda r}$, $Z[\Lambda,m,r] = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right)Y[\Lambda,m,r]$, $X[\Lambda,m,r] = \left[-\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right)+m^2\right]Z[\Lambda,m,r]$, where $\xi = \sqrt{\Lambda^2-m^2}$. Λ arises from the monopole form factor. The coefficients $\mathcal{A}(J)=\frac{2}{3}$, $\mathcal{B}(J)=\frac{4}{3}$ and $\mathcal{C}(J)=1$ for J=0 while $\mathcal{A}(J)=-\frac{1}{3}$, $\mathcal{B}(J)=-\frac{2}{3}$ and $\mathcal{C}(J)=1$ for J=2.

The effective potentials of $Y(3930)$ with $J^P=0^+,2^+$ are presented in Fig. 1, where the exchanged mesons include π, η, ρ, ω and σ. For $Y(4143)$, its effective potential is shown in Fig. 2, where both the η and ϕ meson exchange is allowed. Clearly there exists quite strong attraction around 1 fm for both $Y(3930)$ and $Y(4143)$ with $J^P=0^+$. Then we solved the Schrödinger equation to find the binding energy for the $Y(3930)$ and $Y(4140)$ systems. Some typical numerical results are collected in Table I and Fig. 3. We found molecular solutions for $Y(3930)$ and $Y(4140)$ with $J^P=0^+,2^+$. The first line in Table I is added after CDF released their data, which corresponds to the central mass of Y(3930) and Y(4143).



(a) (b)

FIG. 1: The shape of the exchange potential of $Y(3930)$. The thick solid line is the total effective potential. Here we take the cutoff $\Lambda = 1$ GeV.



(a) (b)

FIG. 2: The variation of the effective potential of $Y(4143)$ with r. The thick solid line is the total effective potential. Here we take the cutoff $\Lambda = 1$ GeV.

	$J^P = 0^+$			$J^P = 2^+$		
State	Λ (GeV)	E (MeV)	$r_{\rm rms}$ (fm)	Λ (GeV)	E (MeV)	$r_{\rm rms}$ (fm)
$Y(3930)$	0.48	-97.1	0.84	0.44	-98.9	1.00
	0.49	-71.2	0.92	0.46	-66.4	1.11
	0.50	-49.5	1.03	0.48	-41.9	1.25
	0.51	-31.92	1.21	0.50	-24.0	1.47
	0.52	-18.32	1.48	0.51	-17.23	1.63
	0.53	-8.61	1.95	0.52	-11.71	1.85
	0.54	-2.57	2.76	0.53	-7.36	2.14
$Y(4143)$	0.57	-87.4	0.78	0.48	-81.9	1.03
	0.58	-69.9	0.84	0.49	-68.9	1.07
	0.59	-54.5	0.92	0.51	-47.2	1.19
	0.60	-41.2	1.01	0.52	-38.2	1.26
	0.61	-29.9	1.13	0.53	-30.4	1.35
	0.62	-20.46	1.30	0.54	-23.64	1.46
	0.63	-12.91	1.55	0.55	-17.87	1.60
	0.64	-7.13	1.93	0.56	-13.01	1.77

TABLE I: Some typical numerical results for the $Y(3930)$ and $Y(4143)$ systems.

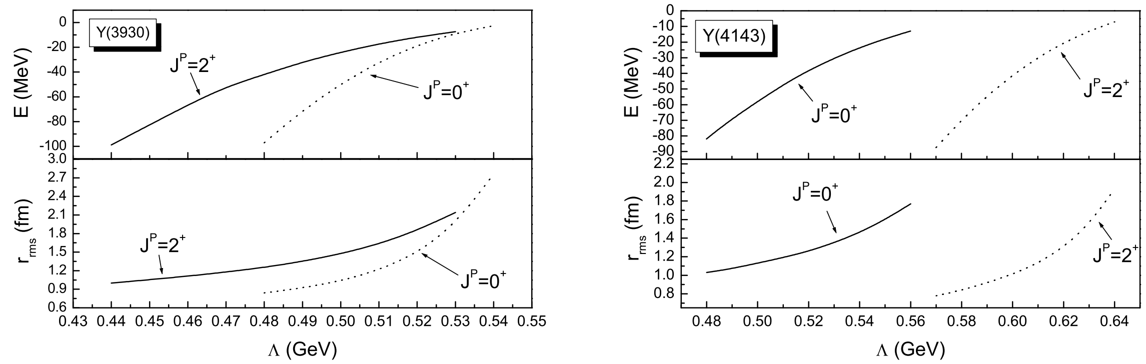


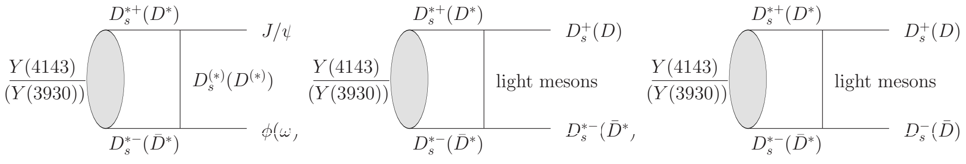
FIG. 3: The variation of the binding energy E and r_{rms} with the cutoff Λ.

III. CHARACTERISTIC DECAY PATTERNS OF $Y(4143)$ AND $Y(3930)$

Now we discuss the possible decay modes of these molecular states.

1. Hidden charm two-body decay
   This is the discovery mode of $Y(3930)$ and $Y(4143)$. This S-wave decay occurs through the rescattering mechanism [10], which is shown in Fig. 4 (a). The branching ratio of the hidden charm decay is strongly suppressed for the conventional excited charmonium around 4 GeV. However, this mode is certainly not suppressed for heavy molecular states. Sometimes, they become one of the dominant decay modes.

2. Open charm two-body decay



(a) (b) (c)

FIG. 4: Rescattering diagram for the hidden and open charm decays of $Y(4143)$ and $Y(3930)$.

At the first sight, one may worry whether the open-charm decays of $Y(3930)$ and $Y(4143)$ overwhelm the hidden decay as in the excited charmonium decays. However, this is not the case for molecular states. In fact, the kinematically allowed modes are $D_s^+D_s^{*-}+h.c./D\bar{D}^*+h.c.$ and $D_s^+D_s^-+h.c./D\bar{D}+h.c.$. These decays can only happen via the exchange of a light meson as shown in Fig. 4 (b) and (c). In other words, the open-charm decay widths are comparable to the hidden-charm width. There are some simple selection rules from the parity and angular momentum conservation. For example, the $J^P=0^+$ state does not decay into $D\bar{D}^*(D_s^+D_s^{*-})$. The $J^P=2^+$ state decays into $D\bar{D}^*(D_s^+D_s^{*-})$ or $D\bar{D}(D_s^+D_s^-)$ through D-wave. Such a D-wave decay width should be much smaller than that for the above hidden charm S-wave decay mode.

3. Open charm three-body and four-body decays
   Another potentially important decay mode is that one or two components of the molecular state decays into a $D\pi$ or DK pair. The possible three- and four-body decay modes of $Y(3930)$ are $\bar{D}^*D\pi$, $\bar{D}D\pi\pi$. For $Y(4143)$, the possible modes are $\bar{D}_s^*DK$, $\bar{D}KDK$. However all these three- and four-body decay modes are kinematically forbidden! The isospin violating modes $\bar{D}_s^*D_s\pi^0$ and $\bar{D}_s\pi^0D_s\pi^0$ are also kinematically forbidden for $Y(4143)$.

4. Radiative decay
   One or both vector mesons can easily decay into the $D\gamma$ or $D_s\gamma$ final states. The typical radiative modes of $Y(3930)$ are $\bar{D}^*D\gamma$, $\bar{D}\gamma D\gamma$, $\bar{D}\pi D\gamma$. For $Y(4143)$ the radiative modes are $\bar{D}_s^*D_s\gamma$, $\bar{D}_s\gamma D_s\pi^0$, $\bar{D}_s\gamma D_s\gamma$. The radiative decay width and the line shape of the photon spectrum are very interesting, which will be pursued in a subsequent work.

5. Semi-leptonic and Non-leptonic decay
   The semi-leptonic and non-leptonic decays via one component of the molecular state also contain useful information of its inner structure.

IV. CONCLUSION

In this paper we have discussed the various assignment of the $Y(4143)$ signal discovered by the CDF collaboration. With the extreme similarity between $Y(3930)$ and $Y(4143)$ in mind, we conclude that both of them are very good molecular states composed of a pair of vector charm mesons, which was predicted in the meson exchange model [1]. $Y(3930)$ and $Y(4143)$ are molecular partners with $J^{PC}=0^{++}$ or 2^{++}. Such a classification neatly explains the narrow width of $Y(4143)$. The hidden charm discovery mode $J/\psi\phi$ naturally becomes one of the dominant decay modes since the kinematically allowed open-charm decays also occur through the same rescattering mechanism. Hence the width of the hidden-charm and open charm decay widths are comparable. Especially for the case of $J^{PC}=2^{++}$ the hidden charm decay is the dominant decay mode since the two-body open charm decay occurs through D-wave.

In short summary, CDF, Babar and Belle collaborations may have discovered heavy molecular states already. We urge our experimental colleagues to confirm Y(4143) and measure its J^P after accumulating more $J\psi\phi$ data, or even in the radiative decays.

In fact the above interpretation helps us to clarify these new charmonium states observed in the past six years:

1. $Z(3930)$ is a 2^{++} charmonium χ_{c2}'';
2. $X(3940)$ may be $\eta_c(3S)$;
3. Both $Y(4143)$ and $Y(3930)$ are probably molecular states;
4. $Y(4260)$ is a good candidate of the hybrid charmonium;
5. $X(3872)$ may be χ_{c1}' or a $\bar{D}D^*$ molecular state;
6. $Z^+(4430)$ could be a molecular candidate however its existence needs further confirmation.

Acknowledgments

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