The analysis of the charmonium-like states $X^*(3860), X(3872), X(3915), X(3930)$ and $X(3940)$ according to its strong decay behaviors.

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Inspired by the newly observed state $X^*(3860)$, we analyze the strong decay behaviors of some charmonium-like states $X^*(3860), X(3872), X(3915), X(3930)$ and $X(3940)$ by the $^3P_0$ model. We carry out our work based on the hypothesis that these states are all being the charmonium systems. Our analysis indicates that $0^{++}$ charmonium state can be a good candidate for $X^*(3860)$ and $1^{++}$ state is the possible assignment for $X(3872)$. Considering as the $3^1S_0$ state, the decay behavior of $X(3940)$ is inconsistent with the experimental data. So, we can not assign $X(3940)$ as the $3^1S_0$ charmonium state by present work. Besides, our analysis implies that it is reasonable to assign $X(3915)$ and $X(3930)$ to be the same state, $2^{++}$. However, combining our analysis with that of Zhou [14], we speculate that $X(3915)/X(3930)$ might not be a pure $c\bar{c}$ systems.

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1 Introduction

Very recently, the Belle Collaboration observed a new charmonium-like state, $X^*(3860)$, by performing a full amplitude analysis of the process $e^+e^-\rightarrow J/\psi DD$ [1]. Its mass is $(3862^{+36}_{-32}+^{30}_{-13}$MeV)/c$^2$) and width is $(201^{+154}_{-68}+^{88}_{-62})$MeV. The $J^{PC}=0^{++}$ hypothesis is favored over the $2^{++}$ assignment at the level of 2.5σ. In reference [2], this state was explained to be a $C\gamma_5 \otimes \gamma_5 C$ type scalar tetraquark state by the method of QCD sum rules(QCDSR). Actually, people once had assigned $X(3915)$ as the $0^{++}$ charmnium state [3, 4], which was observed by Belle, BABAR Collaboration in $B\rightarrow J/\psi\omega K$ decay mode [4, 8]. Its mass and width are listed in Table I.

After $X(3915)$ was suggested to be the $\chi_{c0}$ assignment, it encountered several challenges [9–11]. For example, the decay $\chi_{c0}(2P)\rightarrow D\bar{D}$, which was expected to be the dominant decay mode, has not been observed experimentally. In contrast, the decay mode $X(3915)\rightarrow J/\psi\omega$, which should be OZI(Okubo-Zweig-Iizuka) [13] suppressed, was observed instead in experiments. In addition, the mass splitting of
Mixed Charmonium-Molecule State \([52, 53]\) was explained to be different states such as the charmonium state \([46]\), the molecular state \([49–51]\) and a tetraquark state \([37–41]\). Another important explanation is that \(X(3940)\) was confirmed to be \(\Gamma = (37^{+26}_{-13})\) MeV \([44]\).\(^{1}\) Later, its decay width was confirmed to be \(\Gamma = (37^{+26}_{-15} \pm 8)\) MeV \([45]\). People have also explored the structure of \(X(3940)\) with different kinds of methods such as the light-cone formalism \([46]\), the NRQCD factorization formula \([47, 48]\) and QCDSR \([49, 50]\). According to these studies, there seems to be no doubt that the quantum number of \(X(3940)\) is \(3^1 S_0\). However, its structure is still controversial, which have been explained to be different states such as the charmonium state \([46]\), the molecular state \([49, 51]\) and a tetraquark state \([37, 41]\). Another important explanation is that it was the charmonium state with quantum of \(1^{++}\) \([42, 43]\), which has a dominant decay mode \(D^0\bar{D}^0\).

The mass of this newly observed \(X^*(3860)\) is close to that of another charmonium-like state \(X(3872)\). However, these two hadrons are impossible to be the same state because of its different decay modes and widths(see Table I). After \(X(3872)\) was discovered by Belle Collaboration \([18]\) and confirmed by BABAR \([19]\), CDF \([20]\), D0 \([21]\) and Bell \([22]\) Collaborations, its nature has still been very controversial. It was mainly explained to be such structures as a molecule state \([24–33]\), a hybrid charmonium \([34–36]\), a tetraquark state \([37, 41]\). Another important explanation is that it was the charmonium state with quantum of \(0^{++}\) \([42, 43]\), which has a dominant decay mode \(D^0\bar{D}^0\).

Belle Collaboration reported another charmonium-like state \(X(3940)\) from the inclusive process \(e^+e^- \rightarrow J/\psi + cc\) at a mass of \(M = (3.943 \pm 0.006 \pm 0.006)\) GeV/\(c^2\) \([44]\). After \(X(3872)\) was discovered by Belle Collaboration \([18]\) and confirmed by BABAR \([19]\), CDF \([20]\), D0 \([21]\) and Bell \([22]\) Collaborations, its nature has still been very controversial. It was mainly explained to be such structures as a molecule state \([24–33]\), a hybrid charmonium \([34–36]\), a tetraquark state \([37, 41]\). Another important explanation is that it was the charmonium state with quantum of \(1^{++}\) \([42, 43]\), which has a dominant decay mode \(D^0\bar{D}^0\).

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**TABLE I:** The experimental information about the \(X\) states in this paper.

| States       | Mass(MeV/\(c^2\)) | Width(MeV) | \(J^{PC}\)      | Decay channels         |
|--------------|-------------------|------------|------------------|------------------------|
| \(X^*(3860)\) | 3862^{+26}_{-13} | 201^{+154}_{-67} | 0^{++}(2^3P_0) | \(D\bar{D}\)            |
| \(X(3915)\)  | 3919.4 \pm 2.2  | 13 \pm 6   | 0^{++}(2^3P_0)_1,2^{++}(2^3P_2) | \(J/\psi\)              |
| \(X(3930)\)  | 3929 \pm 5 \pm 2 | 29 \pm 10   | 2^{++}(2^3P_2) | \(D\bar{D}\)            |
| \(X(3940)\)  | 3926.7 \pm 2.7  | 21.3 \pm 6.8 | 2^{++}(2^3P_2) | \(D\bar{D}\)            |
| \(X(3872)\)  | 3872 \pm 0.6  | J/\psi\pi^+\pi^- | \(J/\psi\pi^+\pi^-\) | \(J/\psi\pi^+\pi^-\)    |
| \(X(3872)\)  | 3871.3 \pm 0.7  | J/\psi\pi^+\pi^- | \(J/\psi\pi^+\pi^-\) | \(J/\psi\pi^+\pi^-\)    |
| \(X(3872)\)  | 3871.8 \pm 3.1  | < 2.3      | 1^{++}(2^3P_1) | \(J/\psi\pi^+\pi^-\)    |
| \(X(3872)\)  | 3873.4 \pm 1.4  | J/\psi\pi^+\pi^- | \(J/\psi\pi^+\pi^-\) | \(J/\psi\pi^+\pi^-\)    |
| \(X(3872)\)  | 3875.4 \pm 0.7  | D^0\bar{D}^0\pi^0,J/\psi\omega | \(D^0\bar{D}^0\pi^0,J/\psi\omega\) | \(D^0\bar{D}^0\pi^0\)    |
| \(X(3872)\)  | 3875.6 \pm 0.7  | \(J/\psi\) | \(J/\psi\) | \(J/\psi\) |

In summary, these newly discovered charmonium-like states have inspired many interests about their physical natures. In order to further study its structures, we perform an analysis of the strong decay behaviors of \(X^*(3860), X(3872), X(3915), X(3930)\) and \(X(3940)\) with the \(3^1 P_0\) decay model.
The experimental information about these states are listed in Table I. Since these $X$ states cannot be completely ruled out from the $c\bar{c}$ systems at present, we carry out our calculations by assuming them to be the charmoniums. Our analysis will be helpful to confirm or exclude some $c\bar{c}$ systems and useful to further determine the quantum numbers of the confirmed charmonium states. As for the strong decays of the hadrons, $^3P_0$ decay model \cite{54-56} is an effective method. It has been widely used in this field since it gives a good description of the decay behaviors of many hadrons \cite{57–64}. The article is arranged as follows: In section 2, we give a brief review of the $^3P_0$ decay model; in Sec.3 we study the strong decays of $X^\ast(3860)$, $X(3872)$, $X(3915)$, $X(3930)$ and $X(3940)$; in Sec.4, we present our conclusions.

2 The decay model

The principle of $^3P_0$ decay model is illustrated clearly in Fig.1, where a quark-antiquark pair $q_3\bar{q}_4$ is created from the vacuum with $0^{++}$ quantum numbers. With the $q_1\bar{q}_2$ within the initial meson, this quark systems regroups into two outgoing mesons via quark rearrangement for the meson decay process $A\to BC$. Its transition operator in the nonrelativistic limit reads

$$T = -3\gamma \left( \sum_m (1m1 - m\mid 00) \right) \int d^3p_3d^3p_4\delta^3(\vec{p}_3 + \vec{p}_4)Y^m_1(\vec{\rho}_3)\chi_{1-m\varphi_0}^{34}\omega_0^{34}\chi_3^{34}\bar{b}_3(\vec{p}_3)\bar{d}_4(\vec{p}_4)$$

where $\gamma$ is a dimensionless parameter reflecting the creation strength of the quark-antiquark $q_3\bar{q}_4$ pair. The solid harmonic polynomial $Y^m_1(\vec{\rho}) \equiv |\vec{p}|^1Y^m_{1}(\theta_p, \phi_p)$ reflects the momentum-space distribution of the $q_3\bar{q}_4$.

The helicity amplitude of the decay process $A \to BC$ in the parent meson $A$ center of mass frame
is

\[ \mathcal{M}^{M_A M_B M_C}(\vec{p}) = \gamma \sqrt{8E_A E_B E_C} \sum_{M_L A M_S A} \langle L_A M_L A S_A M_S A | J_A M_J A \rangle \langle L_B M_L B S_B M_S B | J_B M_J B \rangle \]

\times \langle L_C M_L C S_C M_S C | J_C M_J C \rangle \langle 1m1 - m | 00 \rangle \langle \chi_{S_B}^{14} \chi_{S_C}^{32} | \chi_{S_A}^{12} \chi_{14}^{34} \rangle

\times \langle [\phi_B^{14} \phi_C^{32} | \phi_A^{12} \phi_0^{34} ] I(\vec{p}, m_1, m_2, m_3)

+ (-1)^{1+S_A + S_B + S_C} \langle [\phi_B^{14} \phi_C^{32} | \phi_A^{12} \phi_0^{34} ] I(-\vec{p}, m_2, m_1, m_3) \rangle, \]

(2)

where \( I(\vec{P}, m_1, m_2, m_3) \) is the spatial integral which is defined as

\[ I(\vec{P}, m_1, m_2, m_3) = \int d^3 \vec{p} \psi_{n_B L_B M_L B}^* \psi_{n_C L_C M_L C} \psi_{n_A L_A M_L A} \]

\times \psi_{n_A L_A M_L A} (\vec{p}_B + \vec{p}) \Psi_{n_L M_L}^n (\vec{p}) \]

(3)

where \( \vec{P} = \vec{P}_B - \vec{P}_C, \vec{p} = \vec{p}_3, m_3 \) is the mass of the created quark \( q_3 \). We employ the simple harmonic oscillator (SHO) approximation as the meson space wave functions in Eq.(3).

\[ \Psi_{n_L M_L}^n (\vec{p}) = (-1)^n (\lambda)^{L+\frac{z}{2}} \sqrt{\frac{2n!}{\Gamma(n + L + \frac{z}{2})}} \exp \left( -\frac{R^2 p^2}{2} \right) \Psi_{L M_L} (\vec{p}) \]

(4)

where \( R \) is the scale parameter of the SHO. With the Jacob-Wick formula, the helicity amplitude can be converted into the partial wave amplitude

\[ \mathcal{M}^{JL}(\vec{P}) = \frac{\sqrt{4\pi(2L + 1)}}{2J + 1} \sum_{M_{J B} M_{J C}} \langle L0 | J_A M_J A \rangle \langle J_B M_J B J_C M_J C | J_M J A \rangle \mathcal{M}^{M_A M_B M_C}(\vec{P}) \]

(5)

where \( M_{J A} = M_{J B} + M_{J C}, J_A = J_B + J_C \) and \( J_A + J_P = J_B + J_C + J_L \). Finally, the decay width in terms of partial wave amplitudes is

\[ \Gamma = \frac{\pi}{M_A^2} \sum_{J_L} |\mathcal{M}^{JL}|^2 \]

(6)

where \( \vec{P} = |\vec{P}| = \sqrt{[M_A^2 - (M_B + M_C)^2][M_A^2 - (M_B - M_C)^2]} \), \( M_A, M_B, \) and \( M_C \) are the masses of the meson \( A, B, \) and \( C \), respectively.

3 The results and discussions

The decay width based on the \(^3P_0\) model depends on the following input parameters, the light quark pair\((q\bar{q})\) creation strength \( \gamma \), the SHO wave function scale parameter \( R \), and the masses of the mesons and the constituent quarks. The adopted masses of the hadrons are listed in TABLE II, and \( m_u = m_d = 0.22 \text{ GeV}, m_s = 0.419 \text{ GeV} \) and \( m_c = 1.65 \text{ GeV} \). As for the scale parameter \( R \), there are mainly two kinds of choices which are the common value and the effective value. The effective value can be fixed to reproduce the realistic root mean square radius by solving the Schrodinger equation with the linear potential. For the \( \bar{c}c \) systems, the \( R \) value of \( 2P \) states is estimated to be...
TABLE II: The adopted masses of the hadrons used in our calculations.

| States     | $M_{X^*,(3860)}$ | $M_{X,(3872)}$ | $M_{X,(3915)}$ | $M_{X,(3930)}$ | $M_{X,(3940)}$ |
|------------|------------------|----------------|----------------|----------------|----------------|
| Mass(MeV)  | 3862 [1]         | 3872 [18]      | 3919 [4]       | 3927 [16]      | 3942 [44, 45]  |

| States     | $M_{D^0}$ | $M_{D^+}$ | $M_{D^{*+}}$ | $M_{D^{*0}}$ |
|------------|-----------|-----------|--------------|-------------|
| Mass(MeV)  | 1869.6    | 1864.83   | 2010         | 2007        |

2.3 $\sim$ 2.5GeV$^{-1}$ \[68\]. For the mesons $D$ and $D^*$, its value is taken to be $R_{D^0[D^+]} = 1.52$GeV$^{-1}$, $R_{D^{*0}[D^{*+}]} = 1.85$GeV$^{-1}$ \[66, 68\] in this work. Finally, we choose the value of $\gamma$ to be 6.25 for the creation of the u/d quark following Ref. [57].

We know that $X^*(3860)$ was favored to be the $0^{++}(2^3P_0)$ charmonium-like state by Bell Collaboration and $X(3915)$ had also once been explained to be this assignment. Lately, the latter one was corrected to be the same state as another charmonium-like state, $X(3930)$ which had been determined to be $2^{++}(2^3P_2)$ assignment. In order to further confirm these conclusions, we study the strong decay behaviors of $X^*(3860)$ by considering it as the $2^3P_0$ and $2^3P_2$ charmoniums. And so does for the $X(3915)$ state. Besides, we also perform an analysis of the decay behaviors of $X(3930)$, $X(3872)$ and $X(3940)$ which have been favored to be $2^{++}(2^3P_2)$, $1^{++}(2^3P_1)$ and $0^{-+}(3^1S_0)$ states, respectively. As mentioned in Ref. [4], the mass difference $M_{X(3930)} - M_{X(3915)} = 9.7 \pm 3.7$ MeV, is smaller than the fine splitting of $1P$ states $M_{\chi^c_2} - M_{\chi^c_0} = 141.45 \pm 0.32$MeV \[17\]. This is an important evidence to recognizing $X(3915)$ and $X(3930)$ as the same state. In order to determine its mass precisely, we also calculate the decay widths of $2^3P_2(\chi^c_2)$ state on different masses. All of the results are illustrated in the form of graphs, which can be seen from Figures 2 to 9.

![Figure 2](image1.png)

**FIG. 2:** The strong decay of $X^*(3860)$ as the $0^{++}(2^3P_0)$ state on scale parameter $R_{X^*,(3860)}$.

![Figure 3](image2.png)

**FIG. 3:** The strong decay of $X^*(3860)$ as the $2^{++}(2^3P_2)$ state on scale parameter $R_{X^*,(3860)}$.

Whether we consider $X^*(3860)$ as $0^{++}$ or $2^{++}$ charmonium state, there is only one strong decay mode, $X(3860) \rightarrow D\bar{D}$, where $D$ refers to either $D^0$ or $D^+$. From Figures 2 and 3, we can clearly...
see the deference between the total decay widths of these two states. Taking $R = 2.3 \sim 2.5$ GeV$^{-1}$ discussed above, the total strong decay width of $0^{++}$ state ranges from 110 to 180 MeV, which is compatible with the experimental data in Ref. [1]. The total decay width of $2^{++}$ state, which ranges from 0.4 $\sim$ 1.9 MeV, is much smaller than the experimental data. That means, if we assume $X^*(3860)$ as the $0^{++}$ charmonium state, its dominant decay mode and total decay width is consistent well with the experimental data. Thus, our present work support $X^*(3860)$ as the $0^{++}(\chi_c0)$ charmonium state.

Considering $X(3915)$ as the $0^{++}$ and $2^{++}$ charmonium respectively, we also observe different strong decay behaviors from Figures 4 and 5. For the $0^{++}$ state, the total strong decay width ranges from 159 to 220 MeV, which dominantly decays into $D\bar{D}$. Not only its total decay width but also the dominant decay channel is inconsistent with the experimental data in Ref. [4](See Table I). This means that the $X(3915)$ was assumed to be the charmonium state $0^{++}$ is disfavored. If it is treated as the $2^{++}$ charmonium, its decay behavior is very similar with that of $X(3930)$(See Figures 5 and 6). They both decay into $D\bar{D}$ and $D\bar{D}^*$ with the total decay width ranging from 1.0 to 3.0 MeV. In addition, these
values of the decay widths fall in the range of the experimental data. Thus, it seems reasonable to assign both $X(3915)$ and $X(3930)$ to be the the $2^{++}(\chi_{c2})$ charmonium state. If this conclusion is true, the mass of the $\chi_{c2}$ charmonium state has errors. So, we plot the relations of the strong decay widths on the masses of $\chi_{c2}(2^{++})$ in Figure 7, which will be helpful to determine its mass in the experimental and theoretical explorations in the future.

Since the decay width of $\chi_{c2} \to D \bar{D}$ is larger than 1MeV, it should be observable in experiments for both $X(3930)$ and $X(3915)$. However, it was reported by both Bell and Babar Collaborations that the $X(3930)$ and $X(3915)$ were observed in two different decay channels, $X(3930) \to D \bar{D}$ and $X(3915) \to J/\psi \omega$. A reanalysis presented in Ref. [14] shows that if helicity-2 dominance assumption is abandoned and a sizable helicity-0 component is allowed, the decay process $X(3915) \to D \bar{D}$ may be reproduced in the experimental data. But the large helicity-0 contribution means that $X(3930)/X(3915)$ might not be a pure $c\bar{c}$ charmonium state.

Since $X(3872)$ was observed, there have accumulated abundant experimental information, which can be seen in Table I. Belle experiment indicated $B(X(3872) \to D^0 \bar{D}^0 \pi^0 K^+) = 9.4^{+3.6}_{-4.3} B(X(3872) \to J/\psi \pi^+ \pi^- K^+)$ [22]. Based on these experimental data, we can draw a conclusion that $D^0 \bar{D}^0$ is the dominant decay of $X(3872)$. Although the underlying structure of this state is very controversial, there is no doubt that its quantum number is $1^{++}$. As a charmonium state $\chi_{c1}(1^{++})$, we show the dependence of the strong decay width on the scale parameter $R$ in Figure 8. Taking $R = 2.3 - 2.5$GeV$^{-1}$, the decay width of the inclusive decay channel $D^0 \bar{D}^0$ ranges from 0.2 to 1.0MeV, which falls in the range of the experimental data in Table I and is also consistent with the conclusion of $D^0 \bar{D}^0$ being the dominant decay mode. Thus, our present work implies that $X(3872)$ is assigned to be the $\chi_{c1}(1^{++})$ charmonium state is reasonable.

Finally, we can see in Figure 9 that, as a $3^{1}S_0$ charmonium state, $X(3940)$ can decay into $D^{*0}D^0$ and $D^{*+}D^-$ final states. This result is consistent with the experiments, where $X(3940)$ was truly

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8.png}
\caption{The strong decay of $X(3872)$ as the $1^{++}(2^3P_1)$ state on scale parameter $R_X(3872)$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{The strong decay of $X(3940)$ as the $0^{-+}(3^1S_0)$ state on scale parameter $R_X(3940)$.}
\end{figure}
observed from the inclusive process $e^+e^- \rightarrow J/\psi D^0 D$. However, it can also be seen from Figure 9 that the maximum of the total decay width can only reach up to 10MeV if $R$ is changed from 2.0 to 3.0GeV$^{-1}$. The predicted decay width in experiments is $\Gamma = 37^{+26}_{-15} \pm 8$MeV which is much larger than this value. This comparison indicates that $3^1S_0$ charmonium state might not be a good candidate for the $X(3940)$.

4 Conclusion

In summary, by considering both $X^*(3860)$ and $X(3915)$ as $0^{++}$ and $2^{++}$ charmonium states, $X(3872)$, $X(3930)$, $X(3940)$ as $1^{++}$, $2^{++}$ and $0^{-+}$ charmonium separately, we study its two-body open charm strong decay behaviors by the $^3P_0$ decay model. According to comparing our results with the experimental data, we find that $X^*(3860)$ and $X(3872)$ can be explained to be the $\chi_{c0}(2^3P_0)$ and $\chi_{c1}(2^3P_1)$ charmonium state separately. The decay width of $X(3940)$ is inconsistent with the experimental data if it is supposed to be a $3^1S_0$ charmonium state. Thus, $3^1S_0$ charmonium state can be ruled out as a candidate for $X(3940)$. Treated as a $0^{++}$ charmonium, the decay behavior of $X(3915)$ is contradictory to experimental data. This indicates that $X(3915)$ is unlikely to be a $0^{++}$ charmonium state. Supposed as a $2^{++}$ charmonium, the decay behavior of $X(3915)$ is consistent with not only the experimental data by also that of $X(3930)$. Thus, we tentatively assign these two states as the same charmonium $\chi_{c2}$. According to a reanalysis of the experimental data, Zhou [14] also suggested them to be the same state $2^{++}$, but with a significant non-cc component. As a result, the structure of $X(3915)/X(3930)$ needs to be further studied according to more experimental and theoretical explorations.

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[10] S. L. Olsen, Phys. Rev. D 91, 057501 (2015).
[11] E. J. Eichten, K. Lane, and C. Quigg, Phys. Rev. D 73, 014014 (2006).
[12] Z.G. Wang, Eur. Phys. J. C 77, 78(2017); Eur. Phys. J. A 53, 19(2017).
[13] S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, CERN Report Th 401 and 412 (1964); J. Iizuka, K. Okada and O. Shito, Prog. Theor. Phys. 35, 1061 (1966); J. Iizuka, Prog. Theor. Phys. Suppl. 37, 21 (1966).
[14] Z. Y. Zhou, Z. Xiao and H. Q. Zhou, Phys. Rev. Lett. 115, 022001 (2015).
[15] S.Uehara et al.(Bell Collaboration),Phys.Rev.Lett.96,082003(2006).
[16] B.Aubert et al.(BABAR Collaboration),Phys.Rev.D81,092003(2010).
[17] J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
[18] S.K. Choi et al., Belle Collaboration, Phys. Rev. Lett. 91, 262001 (2003).
[19] B. Aubert et al., Babar Collaboration, Phys. Rev. D 71, 071103 (2005).
[20] D. Acosta et al., CDFII Collaboration, Phys. Rev. Lett. 93, 072001 (2004).
[21] V.M. Abazov et al., D0 Collaboration, Phys. Rev. Lett. 93, 162002 (2004).
[22] G. Gokhroo et al., Belle Collaboration, Phys. Rev. Lett. 97, 162002 (2006).
[23] Babar Collaboration, talk given by P. Grenier in Moriond QCD 2007, 17-24 March, http://moriond.in2p3.fr/QCD/2007/SundayAfternoon/Grenier.pdf
[24] F.E. Close, P.R. Page, Phys. Lett. B 578, 119 (2004).
[25] M.B. Voloshin, Phys. Lett. B 579, 316 (2004).
[26] C.Y. Wong, Phys. Rev. C 69, 055202 (2004).
[27] E.S. Swanson, Phys. Lett. B 588, 189 (2004); ibid B 598, 197 (2004).
[28] N.A. Tornqvist, Phys. Lett. B 590, 209 (2004).
[29] Mohammad T. AlFiky, Fabrizio Gabbiani, Alexey A. Petrov, Phys.Lett. B 640, 238-245(2006).
[30] A.B. Larionov, M. Strikman, M. Bleicher, Phys. Lett. B 749, 35-43 (2015).
[31] Z.G.Wang, T. Huang, Eur.Phys.J.C 74,2891 (2014).
[32] A. Esposito, A. Pilloni, and A.D. Polosa, Phys. Rept. 668, 1 (2017).
[33] Xian-Wei Kang and J. A. Oller, arXiv:1612.08420[hep-ph](2016).
[34] B.A. Li, Phys. Lett. B 605, 306 (2005).
[35] M. Nielsen, C.M. Zanetti, Phys.Rev.D 82, 116002 (2010).
[36] M. Takizawa, S. Takeuchi, arXiv:1206.4877[hep-ph].
[37] Y. Cui, X.L. Chen, W.Z. Deng, S.L. Zhu, High Energy Phys. Nucl. Phys. 31, 7 (2007).
[38] R.D. Matheus, S. Narison, M. Nielsen, J.M. Richard, Phys. Rev. D 75, 014005 (2007).
[39] T.W. Chiu, T.H. Hsieh, Phys. Lett. B 646, 95 (2007).
[40] S.Dubnicka, A.Z.Dubnickova, M.A.Ivanov, and J.G.Korner, Phys.Rev.D 81,114007(2010).
[41] Z.G.Wang, T. Huang,Phys. Rev. D 89, 054019 (2014).
[42] N. N. Achasov and E. V. Rogozina, Mod. Phys. Lett. A 30, 1550181 (2015).
[43] Wei-Jun Deng, Hui Liu, Long-Cheng Gui, and Xian-Hui Zhong, Phys. Rev. D 95, 034026 (2017).
[44] K.Abe (Bell Collaboration)Phys. Rev. Lett. 98, 082001 (2007).
[45] P.Pakhlov, (Bell Collaboration)Phys. Rev. Lett. 100, 202001 (2008).
[46] V. V. Braguta, A. K. Likhoded, A. V. Luchinsky, Phys. Rev. D 74, 094004 (2006).
[47] R.L.Zhu, Phys. Rev. D 92, 074017 (2015).
[48] Z.G.He, B.Q.Li, Phys.Lett.B 693, 36-43(2010).
[49] R. M. Albuquerque, M. E. Bracco and M. Nielsen, Phys. Lett. B 678, 186 (2009) [arXiv:0903.5540 [hep-ph]].
[50] Z.G.Wang Eur.Phys.J.C 74, 2963 (2014).
[51] X. Liu and S. -L. Zhu, Phys. Rev. D 80, 017502 (2009).
[52] R.M. Albuquerque, J.M. Dias, M. Nielsen, C.M. Zanetti, Phys. Rev. D 89, 076007 (2014).
[53] F. Fernandez, P. G. Ortega, D. R. Entem, AIP Conf. Proc. 1606, 168 (2014).
[54] L. Micu, Nucl. Phys. B10, 521 (1969).
[55] R. Carlitz and M. Kislinger, Phys. Rev. D 2, 336 (1970); E.W. Colglazier and J. L. Rosner, Nucl. Phys. B27, 349 (1971); W. P. Petersen and J. L. Rosner, Phys. Rev. D 6, 820 (1972).
[56] A. Le Yaouanc, L. Oliver, O. Pene, and J.-C. Raynal, Phys. Rev. D 8, 2223 (1973); 9, 1415 (1974); 11, 1272 (1975); Phys. Lett. B 71, 397 (1977); A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Phys. Lett. B 72, 57 (1977).
[57] H. G. Blundell, [arXiv:hep-ph/9608473] H. G. Blundell and S. Godfrey, Phys. Rev. D 53, 3700 (1996); H. G. Blundell, S. Godfrey, and B. Phelps, Phys. Rev. D 53, 3712 (1996).
[58] H. Q. Zhou, R. G. Ping, and B. S. Zou, Phys. Lett. B 611, 123 (2005).
[59] D.-M. Li and S. Zhou, Phys. Rev. D 78, 054013 (2008); D.-M. Li and E. Wang, Eur. Phys. J. C 63, 297 (2009); D.-M. Li, P.-F. Ji, and B. Ma, Eur. Phys. J. C 71, 1582 (2011).
[60] B. Zhang, X. Liu, W. Z. Deng, and S. L. Zhu, Eur. Phys. J. C 50, 617 (2007); Y. Sun, Q. T. Song, D. Y. Chen, X. Liu, and S. L. Zhu, Phys. Rev. D 89, 054026 (2014).
[61] E. S. Ackleh, T. Barnes, and E. S. Swanson, Phys. Rev. D 54, 6811 (1996); T. Barnes, N. Black, and P. R. Page, Phys. Rev. D 68, 054014 (2003); T. Barnes, S. Godfrey, and E. S. Swanson, Phys. Rev. D 72, 054026 (2005).
[62] F. E. Close and E. S. Swanson, Phys. Rev. D 72, 094004 (2005); F. E. Close, C. E. Thomas, O. Lakhina, and E. S. Swanson, Phys. Lett. B 647, 159 (2007).
[63] J. Ferretti, G. Galata, and E. Santopinto, Phys. Rev. C 88, 015207 (2013); J. Ferretti, G. Galata, and E. Santopinto, Phys. Rev. D 90, 054010 (2014); J. Ferretti and E. Santopinto, Phys. Rev. D 90, 094022 (2014).
[64] YU Guo-Liang, WANG Zhi-Gang, LI Zhen-Yu, MENG Gao-Qing, Chin. Phys. C 39, 063101 (2015); Guo-Liang Yu, Zhi-Gang Wang, Zhen-Yu Li, Phys. Rev. D 94, 074024 (2016).
[65] C. Patrignani et al. (Particle Data Group), Chin. Phys. C 40, 100001 (2016).
[66] S. Godfrey and R. Kokoski, Phys. Rev. D 43, 1679 (1991).
[67] B-Q. Li, and K-T. Chao, Phys. Rev. D 79, 094004 (2009).
[68] You-chang Yang, Zurong Xia, and Jialun Ping, Phys. Rev. D 81, 094003 (2010).