

Investigations on the charmless decays of $Y(4260)$ *

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Abstract: Apart from the charmed decay channels of $Y(4260)$, the charmless decay channels of $Y(4260)$ also provide us a good platform to study the nature and the decay mechanism of $Y(4260)$. In this paper, we propose to probe the structure of $Y(4260)$ through the charmless decays $Y(4260) \rightarrow VP$ via intermediate $D_1\bar{D}+c.c.$ meson loops, where V and P stand for light vector and pseudoscalar mesons, respectively. Under the molecule ansatz of $Y(4260)$, the predicted total branching ratio BR_{VP} for all $Y(4260) \rightarrow VP$ processes are about $(0.34^{+0.32}_{-0.23})\%$ to $(0.75^{+0.72}_{-0.52})\%$ with the cutoff parameter $\alpha=2-3$. Numerical results show that the intermediate $D_1\bar{D}+c.c.$ meson loops may be a possible transition mechanism in the $Y(4260) \rightarrow VP$ decays. These predicted branching ratios are the same order to that of $Y(4260) \rightarrow Z_c^+(3900)\pi^-$, which may be an evidence of D_1D molecule and can be examined by the forthcoming BESIII data in the near future.

Key words: intermediate meson loop, exotic states

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1 Introduction

In the past decade, many new charmonium (or charmoniumlike) states, i.e., the so-called XYZ states, have been observed experimentally, which has triggered a lot of theoretical investigations on the nature of exotic meson resonances beyond the conventional $q\bar{q}$ quark model [1–6]. Among these observed XYZ states, the resonance $Y(4260)$, which was first observed by the BaBar Collaboration in the $\pi^+\pi^-J/\psi$ invariant spectrum in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-J/\psi$ [7], and then confirmed by both the CLEO and Belle collaborations [8, 9], is a very interesting one because of that its mass $m=4263^{+8}_{-9}$ MeV [10] is only about 30–40 MeV below the S -wave $D_1\bar{D}+c.c.$ threshold. And very recently, the new data from BESIII confirms the signal in $Y(4260) \rightarrow J/\psi\pi^+\pi^-$ with much higher statistics [11]. It indicates that it is worth studying the structure and decays of $Y(4260)$.

Since the observation of $Y(4260)$, many different

solutions have been proposed to study the structure of $Y(4260)$. These solutions include the $4S$ charmonium [12], tetraquark $c\bar{c}s\bar{s}$ state [13], charmonium hybrid [14–16], $D_1\bar{D}$ molecule [17–19]³⁾, $\chi_{c1}\omega$ molecule [23], $\chi_{c1}\rho$ molecule [24], hadrocharmonium state [4, 25, 26], spin-triplet $\Lambda_c-\Lambda_c$ baryonium states [27–30], a cusp [31, 32] or a non-resonance explanation [33, 34]. Under the $D_1\bar{D}$ molecule ansatz, some experimental observations can be described, such as the observation of $Z_c(3900)$ in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ [19], the production of $X(3872)$ in the e^+e^- annihilation around the mass of $Y(4260)$ [20], and the threshold behavior in the main decay channels of $Y(4260)$ [35] etc. In Ref. [26], Li and Voloshin argue that the hadrocharmonium interpretation of $Y(4260)$ may be more credible. Their argument is based on the fact that the production of S -wave pairs with $S_L^P = (3/2)^+$ and $S_L^P = (1/2)^-$ heavy mesons, where S_L is the sum of the spin of the light quark and the orbital angular momentum in the heavy mesons, is forbidden in e^+e^- collisions

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3) There are two D_1 states of similar masses, and the one in question should be the narrower one, i.e., the $D_1(2420)$ ($\Gamma=27$ MeV), the $D_1(2430)$ ($\Gamma\approx 384$ MeV) is too broad to form a molecular state [20–22].



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in the limit of exact heavy quark spin symmetry. In Ref. [26], it was also shown that both the rescattering due to the process $D^*\bar{D}^* \rightarrow D_1\bar{D}$ and the mixing of the $D_1(2420)$ with the $D_1(2430)$ cannot evade this suppressed production. They also considered the possible kinematic effects that might increase the amount of the heavy quark spin symmetry (HQSS) violation and found that the kinematical effect is quite small at such energy. Thus, they concluded that S -wave $D_1\bar{D}$ production is suppressed. In Ref. [36], Wang et al. tackle both the hadronic molecule and the hadrocharmonium interpretations of the $Y(4260)$ with the experimental data currently available. Although the production of $(3/2)^+$ and $(1/2)^-$ heavy meson pairs is suppressed in the heavy quark limit [26], the heavy quark spin symmetry breaking effects in the charm sector can be significant. So the resulting suppression for the physical charm quark mass is not in conflict with the interpretation that the main component of the $Y(4260)$ is a $D_1\bar{D}$ molecule.

On the other hand, the intermediate meson loop transition as an important nonperturbative dynamical mechanism has been extensively studied in the energy region of charmonium [37–64]. It is widely recognized that the intermediate meson loops may be closely related to some nonperturbative phenomena observed in experiments [46–67], e.g. sizeable branching ratios for non- $D\bar{D}$ decay of $\psi(3770)$ [46–52], the helicity selection rule violations in charmonium decays [59–61], isospin symmetry breaking in charmonium decays [63, 64]. Recently, this intermediate meson loops mechanism has been applied to the production and decays of ordinary and exotic states [19, 20, 35, 68–73].

Recently, the charmful decay channels have been extensively used to constrain the reaction mechanism and gain insights into the nature $Y(4260)$ [35, 68–70]. Apart from the charmful decay channels of $Y(4260)$, the charmless decay channels of $Y(4260)$ are also a good platform to further study $Y(4260)$. In the present work, we study the charmless decays $Y(4260) \rightarrow VP$ via $D_1\bar{D}$ loop with an effective Lagrangian approach (ELA) under the $D_1\bar{D}+c.c.$ molecule ansatz. The paper is organized as follows. In Section 2, we will briefly introduce the ELA and give some relevant formulae, the numerical results are presented in Section 3, and Section 4 contains a brief summary.

2 The model

Generally speaking, all the possible intermediate meson exchange loops should be included in the calculation. In reality, the breakdown of the local quark-hadron duality allows us to pick up the leading contributions as a reasonable approximation [74, 75]. For example, the intermediate states involving flavor changes turn out to be

strongly suppressed. One reason is because of the large virtualities involved in the light meson loops. The other is because of the Okubo-Zweig-Iizuka-rule suppressions. In this work, we have assumed that $Y(4260)$ is dominated by the S -wave $D_1\bar{D}+c.c.$ component and the $D_1\bar{D}+c.c.$ mass threshold is only 30 MeV above the $Y(4260)$, so we consider the S -wave $D_1\bar{D}$ meson loops as the leading contributions.

By assuming $Y(4260)$ is an S -wave $D_1\bar{D}$ molecular state, the effective Lagrangian is constructed as

$$\mathcal{L}_{Y(4260)D_1\bar{D}} = i \frac{x}{\sqrt{2}} (\bar{D}_a^\dagger Y^\mu D_{1a}^{\mu\dagger} - \bar{D}_{1a}^{\mu\dagger} Y^\mu D_a^\dagger) + \text{H.c.}, \quad (1)$$

where x is the coupling constant.

For a state slightly below an S -wave two-hadron threshold, the effective coupling constant of this state to the two-body channel, g_{NR} , is related to the probability of finding the two-hadron component in the physical wave function of the bound state, c^2 , and the binding energy, $\epsilon = m_1 + m_2 - M$ [20, 76, 77]

$$g_{\text{NR}}^2 \equiv 16\pi(m_1 + m_2)^2 c^2 \sqrt{\frac{2\epsilon}{\mu}} [1 + \mathcal{O}(\sqrt{2\mu\epsilon r})], \quad (2)$$

where $\mu = m_1 m_2 / (m_1 + m_2)$ is the reduced mass, and r denotes the range of the forces. Notice that the coupling constant gets maximized for a pure bound state, which has $c^2 = 1$ by definition.

Using the masses of the $Y(4260)$, D and D_1 given in PDG [10], we obtain the mass difference between the $Y(4260)$ and the $D_1\bar{D}+c.c.$ threshold to be $m_{D_1\bar{D}} + m_{D_1} - m_Y = 27_{-8}^{+9}$ MeV. Assuming that $Y(4260)$ is pure DD_1 molecule, which corresponds to the probability of finding a $D_1\bar{D}$ component in the physical wave function of the bound states $c^2 = 1$, we obtain the coupling constant x

$$|x| = 14.62_{-1.25}^{+1.11} \pm 6.20 \text{ GeV}, \quad (3)$$

where the first errors are due to the uncertainties of the binding energies, and the second ones are from the approximate nature of Eq. (2).

The effective Lagrangian relevant to the light vector mesons can be obtained as follows [78, 79],

$$\begin{aligned} \mathcal{L}_V = & ig_{D^*\bar{D}V} \epsilon_{\alpha\beta\mu\nu} (\overleftrightarrow{D}_\alpha^\dagger \overleftrightarrow{D}^{*\beta\dagger} - \overleftrightarrow{D}^{*\beta\dagger} \overleftrightarrow{D}_\alpha^\dagger) \partial^\mu \mathcal{V}^\nu \\ & + ig_{\bar{D}^*\bar{D}V} \epsilon_{\alpha\beta\mu\nu} (\overleftrightarrow{\bar{D}}_\alpha^\dagger \overleftrightarrow{\bar{D}}^{*\beta\dagger} - \overleftrightarrow{\bar{D}}^{*\beta\dagger} \overleftrightarrow{\bar{D}}_\alpha^\dagger) \partial^\mu \mathcal{V}^\nu \\ & + \text{H.c.}, \end{aligned} \quad (4)$$

and the effective Lagrangian for the light pseudoscalar mesons are constructed based on both heavy quark spin-flavor transformation and chiral transformation [80–83]. Accordingly, the interaction terms studied in the present work read

$$\begin{aligned} \mathcal{L}_P = & g_{D_1 D^* P} [3D_1^\mu (\partial_\mu \partial_\nu \mathcal{P}) D^{*\dagger\nu} - D_1^\mu (\partial^\nu \partial_\nu \mathcal{P}) D_\mu^{*\dagger}] \\ & + g_{\bar{D}_1 \bar{D}^* P} [3\bar{D}_1^{*\mu} (\partial_\mu \partial_\nu \mathcal{P}) \bar{D}_1^\nu - \bar{D}_1^{*\mu} (\partial^\nu \partial_\nu \mathcal{P}) \bar{D}_{1\nu}] \\ & + \text{H.c.}, \end{aligned} \quad (5)$$

Before proceeding to the numerical results, we first discuss the possible uncertainties involved in the calculations. The first uncertainty is the assumption of the probability $c^2=1$ for the $D_1\bar{D}$ structure for $Y(4260)$. As shown in Eq. (2), the predicted branching ratios are proportional to probability c^2 . The second one comes from the width effects of $Y(4260)$ and the final ρ mesons. We have checked that the width effect of ρ meson causes only a minor change of about 1%–5%, which is because the mass of the final states are about 3 GeV below $Y(4260)$.

In Fig. 2, we present the total branching ratio of all possible $Y(4260)\rightarrow VP$ in terms of the cutoff parameter α . The upper and lower limits are obtained with the upper and lower limits of the coupling constant in (3). As shown from this figure, there is no cusp structure in the curve. This is because the mass of $Y(4260)$ lies below the intermediate $D_1\bar{D}$ threshold. The branching ratios are not drastically sensitive to the cutoff parameter, which indicates a reasonable cutoff of the ultraviolet contributions by the empirical form factors to some extent.

To show the branching ratios of $Y(4260)$ to different VP channels explicitly, we list the predicted branching ratios of $Y(4260)$ for each decay channel with $\alpha = 2.0$ and 3.0 in Table 1, with comparison to the numerical results obtained without a form factor. Notice that the given errors are from the uncertainties of the the coupling constants in Eq. (3). As shown in Table 1, the total branching ratio of $Y(4260)\rightarrow VP$ is about $(8.03^{+7.78}_{-5.52})\%$ without form factor. Obviously, the obtained branching ratio in this way is somewhat larger than expected. In principle, since the $Y(4260)$ is taken to be a $D_1\bar{D}+c.c.$ molecule, so the main decay channel would be $D^*\bar{D}\pi$. This is because the exchanged charmed mesons are usually off-shell, which indicates the necessity of considering the form factor. As shown in the last two columns in Table 1, the total branching ratio of $Y(4260)\rightarrow VP$ are

from $(3.36^{+3.24}_{-2.31})\times 10^{-3}$ to $(7.48^{+7.22}_{-5.16})\times 10^{-3}$ with the cutoff parameter $\alpha=2.0-3.0$.

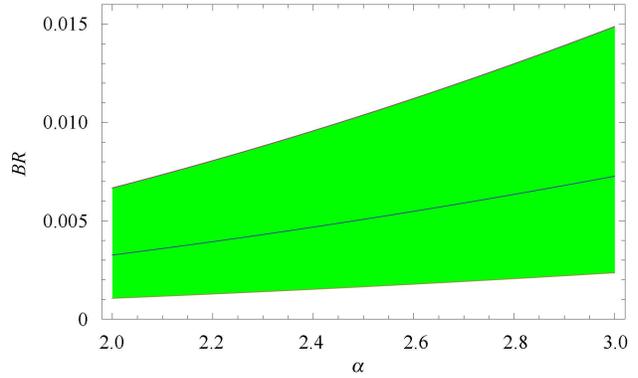


Fig. 2. The α dependence of the total branching ratios of $Y(4260)\rightarrow VP$. The upper and lower limits are obtained with the upper and lower limits of the coupling constant in Eq. (3).

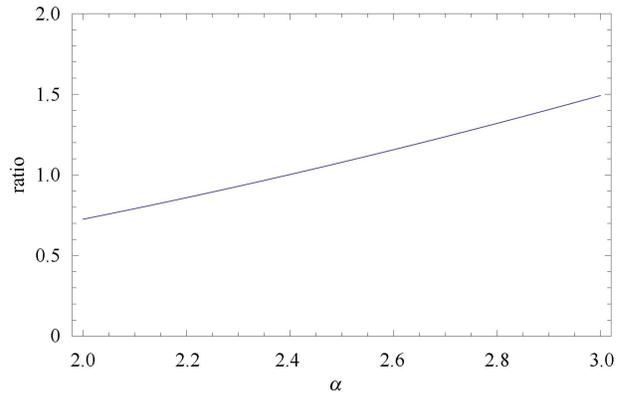


Fig. 3. The α dependence of the total branching ratios of $Y(4260)\rightarrow VP$. The upper and lower limits are obtained with the upper and lower limits of the coupling constant in Eq. (3).

Table 1. The predicted branching ratios of $Y(4260)$ decays with different α values. The uncertainties are dominated by the use of Eq. (2).

final states	no form factor	monopole form factor	
		$\alpha=2.0$	$\alpha=3.0$
$\rho^0\pi^0$	$(1.46^{+1.41}_{-1.01})\times 10^{-2}$	$(8.93^{+8.58}_{-6.12})\times 10^{-4}$	$(1.98^{+1.91}_{-1.36})\times 10^{-3}$
$\rho\pi$	$(4.39^{+4.25}_{-3.03})\times 10^{-2}$	$(2.61^{+2.51}_{-1.99})\times 10^{-3}$	$(5.92^{+5.72}_{-4.11})\times 10^{-3}$
$K^{*+}K^-+c.c.$	$(4.90^{+4.72}_{-3.37})\times 10^{-3}$	$(1.09^{+1.06}_{-0.76})\times 10^{-4}$	$(3.27^{+3.12}_{-2.25})\times 10^{-4}$
$K^{*0}\bar{K}^-+c.c.$	$(4.96^{+4.78}_{-3.41})\times 10^{-3}$	$(1.44^{+1.38}_{-0.99})\times 10^{-4}$	$(3.21^{+3.09}_{-2.21})\times 10^{-4}$
$\omega\eta$	$(1.37^{+1.33}_{-0.95})\times 10^{-2}$	$(3.63^{+3.51}_{-2.51})\times 10^{-4}$	$(8.18^{+7.88}_{-5.62})\times 10^{-4}$
$\omega\eta'$	$(1.25^{+1.21}_{-0.86})\times 10^{-2}$	$(3.47^{+3.35}_{-2.39})\times 10^{-5}$	$(8.38^{+8.13}_{-5.77})\times 10^{-5}$
$\rho\eta$	$(2.93^{+2.83}_{-2.01})\times 10^{-7}$	$(9.48^{+9.13}_{-6.52})\times 10^{-9}$	$(1.96^{+1.89}_{-1.35})\times 10^{-8}$
$\rho\eta'$	$(8.18^{+7.88}_{-5.62})\times 10^{-7}$	$(3.27^{+3.15}_{-2.25})\times 10^{-8}$	$(6.52^{+6.27}_{-4.41})\times 10^{-8}$
$\omega\pi^0$	$(5.22^{+5.02}_{-3.56})\times 10^{-7}$	$(1.44^{+1.39}_{-1.00})\times 10^{-8}$	$(3.09^{+2.97}_{-2.13})\times 10^{-8}$
total	$(8.03^{+7.78}_{-5.52})\%$	$(3.36^{+3.24}_{-2.31})\times 10^{-3}$	$(7.48^{+7.22}_{-5.16})\times 10^{-3}$

For the isospin-violating channels, i.e., $Y(4260) \rightarrow \omega\pi^0$, $\rho\eta$, and $\rho\eta'$, the charged and neutral charmed meson loops should cancel out exactly in the isospin symmetry limit. In other words, the mass difference between the u and d quark will lead to $m_{\mathcal{D}}^{(*)\pm} \neq m_{\mathcal{D}}^{(*)0}$ due to the isospin symmetry breaking. As a result, the charged and neutral charmed meson loops cannot completely cancel out, and the residue part will contribute to the isospin-violating amplitudes. The branching ratios of these isospin-violating channels as shown in Table 1 are suppressed. Differing from the isospin-violating channels, since there are no cancelations between the charged and neutral meson loops for the isospin conserved channels, i.e., $Y(4260) \rightarrow \rho\pi$, $K^*\bar{K}+c.c.$, $\omega\eta$, and $\omega\eta'$, so the calculated branching ratios of these channels are 3–4 orders of magnitude larger than those of the isospin violated channels. As shown in this table, at the same α , the predicted branching ratios of $Y(4260) \rightarrow \omega\eta$ are one order of magnitude larger than those of $Y(4260) \rightarrow \omega\eta'$. The reasons may attribute to the different $n\bar{n}$ component and different phase space. We suggest experimental measurements to test this point.

In order to better understand the decay mechanism of $Y(4260)$, we define the following ratio

$$R = \frac{Br(Y(4260) \rightarrow VP)}{Br(Y(4260) \rightarrow Z_c^+(3900)\pi^-)}, \quad (14)$$

which is plotted in Fig. 3 for the dependence on the cut-off parameter. The ratio is less sensitive to the cutoff parameter, which is a consequence of the fact that the involved loops are the same. The predicted branching

ratios for $Y(4260) \rightarrow VP$ are the same order to that of $Y(4260) \rightarrow Z_c(3900)\pi$. It may be an evidence for the molecule structure of $Y(4260)$ and can be tested by the experimental measurements in future.

4 Summary

In this work, we have investigated the charmless decays of $Y(4260)$ in ELA, where $Y(4260)$ is considered as a $D_1\bar{D}$ molecular state candidate. We explore the rescattering mechanism with the effective Lagrangian based on the heavy quark symmetry and chiral symmetry. The results show that the branching ratios are not drastically dependent on α . With the commonly accepted $\alpha=2-3$ range, we make a quantitative prediction for all $Y(4260) \rightarrow VP$ with BR_{VP} from $(3.36_{-2.31}^{+3.24}) \times 10^{-3}$ to $(7.48_{-5.16}^{+7.22}) \times 10^{-3}$. These predicted branching ratios are the same order as those of $Y(4260) \rightarrow Z_c^+(3900)\pi^-$ with the molecular state assumption. It indicates that the intermediate $D_1\bar{D}$ meson loops may be a possible mechanism in $Y(4260) \rightarrow VP$ decays. Of course, the relevant calculations of these $Y(4260) \rightarrow VP$ channels in other models are also needed in order to study the nature of $Y(4260)$ in more depth. We expect that with the help of precise measurements of various decay modes at BESIII, the nature of $Y(4260)$ and the decay mechanism of $Y(4260) \rightarrow VP$ can be investigated in depth, and the intermediate meson loops mechanism can be established as a possible nonperturbative dynamics mechanism in the charmonium energy region, especially when the initial states are close to the two particle thresholds.

References

- 1 Brambilla B, Eidelman S, Heltsley B K, Vogt R, Bodwin G T, Eichten E, Frawley A D, Meyer A B et al. *Eur. Phys. J. C*, 2011, **71**: 1534
- 2 Swanson E S. *Phys. Rept.*, 2006, **429**: 243
- 3 Eichten E, Godfrey S, Mahlke H, Rosner J H. *Rev. Mod. Phys.*, 2008, **80**: 1161
- 4 Voloshin M B. *Prog. Part. Nucl. Phys.*, 2008, **61**: 455
- 5 Godfrey S, Olsen S L. *Ann. Rev. Nucl. Part. Sci.*, 2008, **58**: 51
- 6 Drenska N, Faccini R, Piccinini F, Polosa F A, Renga F, Sabelli C, *Riv. Nuovo Cim.*, 2010, **033**: 633
- 7 Aubert B et al. (BABAR collaboration). *Phys. Rev. Lett.*, 2005, **95**: 142001
- 8 HE Q et al. (CLEO collaboration). *Phys. Rev. D*, 2006, **74**: 091104
- 9 YUAN C Z et al. (Belle collaboration). *Phys. Rev. Lett.*, 2007, **99**: 182004
- 10 Olive K A et al. (Particle Data Group collaboration). *Chin. Phys. C*, 2014, **38**: 1
- 11 Ablikim M et al. (BESIII collaboration). *Phys. Rev. Lett.*, 2013, **110**: 252001
- 12 Llanes-Estrada F J. *Phys. Rev. D*, 2005, **72**: 031503
- 13 Maiani L, Riquer V, Piccinini F, Polosa A D. *Phys. Rev. D*, 2005, **72**: 031502
- 14 ZHU S L. *Phys. Lett. B*, 2005, **625**: 212
- 15 Kou E, Pene O. *Phys. Lett. B*, 2005, **631**: 164
- 16 Close F E, Page P R. *Phys. Lett. B*, 2005, **628**: 215
- 17 DING G J, ZHU J J, YAN M L. *Phys. Rev. D*, 2008, **77**: 014033
- 18 DING G J. *Phys. Rev. D*, 2009, **79**: 014001
- 19 WANG Q, Hanhart C, ZHAO Q. *Phys. Rev. Lett.*, 2013, **111**: 132003
- 20 GUO F K, Hanhart C, Meißner U G, WANG Q, ZHAO Q. *Phys. Lett. B*, 2013, **725**: 127
- 21 Filin A A, Romanov A, Baru V, Hanhart C, Kalashnikova Y X, Kudryavtsev A E, Meißner U G, Nefediev A V. *Phys. Rev. Lett.*, 2010, **105**: 019101
- 22 GUO F K, Meißner U G. *Phys. Rev. D*, 2011, **84**: 014013
- 23 YUAN C Z, WANG P, MO X H. *Phys. Lett. B*, 2006, **634**: 399
- 24 LIU X, ZENG X Q, LI X Q. *Phys. Rev. D*, 2005, **72**: 054023
- 25 Dubynskiy S, Voloshin M B. *Phys. Lett. B*, 2008, **666**: 344
- 26 LI X, Voloshin M B. *Phys. Rev. D*, 2013, **88**: 034012
- 27 QIAO C F. *Phys. Lett. B*, 2006, **639**: 263
- 28 QIAO C F. *J. Phys. G*, 2008, **35**: 075008
- 29 CHEN Y D, QIAO C F. *Phys. Rev. D*, 2012, **85**: 034034
- 30 CHEN Y D, QIAO C F, SHEN P N, ZENG Z Q. *Phys. Rev. D*, 2013, **88**: 114007
- 31 van Beveren E, Rupp G. arXiv:0904.4351 [hep-ph]
- 32 van Beveren E, Rupp G. *Phys. Rev. D*, 2009, **79**: 111501
- 33 van Beveren E, Rupp G, Segovia J. *Phys. Rev. Lett.*, 2010, **105**: 102001
- 34 CHEN D Y, HE J, LIU X. *Phys. Rev. D*, 2011, **83**: 054021

- 35 LIU X H, LI G. Phys. Rev. D, 2013, **88**: 014013
- 36 WANG Q, Cleven M, GUO F K, Hanhart C, Meißner U G, WU X G, ZHAO Q. Phys. Rev. D, 2014, **89**: 034001
- 37 LI X Q, Bugg D V, ZOU B S. Phys. Rev. D, 1997, **55**: 1421
- 38 ZHAO Q, ZOU B S. Phys. Rev. D, 2006, **74**: 114025
- 39 ZHAO Q. Phys. Lett. B, 2006, **636**: 197
- 40 LI G, ZHAO Q. Phys. Rev. D, 2011, **84**: 074005
- 41 LI G, LIU X H, ZHAO Q. Eur. Phys. J. C, 2013, **73**: 2576
- 42 LI G, ZHAO Q, CHANG C H. J. Phys. G, 2008, **35**: 055002
- 43 WANG Q, LI G, ZHAO Q. Phys. Rev. D, 2012, **85**: 074015
- 44 LI G, SHAO F L, ZHAO C W, ZHAO Q. Phys. Rev. D, 2013, **87**: 034020
- 45 LI G, ZHAO Q. Phys. Lett. B, 2008, **670**: 55
- 46 Achasov N N, Kozhevnikov A A. Phys. Lett. B, 1991, **260**: 425
- 47 Achasov N N, Kozhevnikov A A. JETP Lett., 1991, **54**: 193; Pisma Zh. Eksp. Teor. Fiz., 1991, **54**: 197
- 48 Achasov N N, Kozhevnikov A A. Phys. Rev. D, 1994, **49**: 275
- 49 Achasov N N, Kozhevnikov A A. Phys. Atom. Nucl., 2006, **69**: 988
- 50 ZHANG Y J, LI G, ZHAO Q. Phys. Rev. Lett., 2009, **102**: 172001
- 51 LIU X, ZHANG BO, LI X Q. Phys. Lett. B, 2009, **675**: 441
- 52 LI G, LIU X H, WANG Q, ZHAO Q. Phys. Rev. D, 2013, **88**: 014010
- 53 WU J J, ZHAO Q, ZOU B S. Phys. Rev. D, 2007, **75**: 114012
- 54 LIU X, ZENG X Q, LI X Q. Phys. Rev. D, 2006, **74**: 074003
- 55 CHENG H Y, CHUA C K, Soni A. Phys. Rev. D, 2005, **71**: 014030
- 56 Anisovich V V, Bugg D V, Sarantsev A V, ZOU B S. Phys. Rev. D, 1995, **51**: 4619
- 57 ZHAO Q, ZOU B S, MA Z B. Phys. Lett. B, 2005, **631**: 22
- 58 LI G, ZHAO Q, ZOU B S. Phys. Rev. D, 2008, **77**: 014010
- 59 LIU X H, ZHAO Q. Phys. Rev. D, 2010, **81**: 014017
- 60 WANG Q, LIU X H, ZHAO Q. Phys. Lett. B, 2012, **711**: 364
- 61 LIU X H, ZHAO Q. J. Phys. G, 2011, **38**: 035007
- 62 GUO F K, Hanhart C, Meißner U G. Phys. Rev. Lett., 2009, **103**: 082003; 2010, **104**: 109901
- 63 GUO F K, Hanhart C, LI G, U. G. Meißner, ZHAO Q. Phys. Rev. D, 2010, **82**: 034025
- 64 GUO F K, Hanhart C, LI G, U. G. Meißner, ZHAO Q. Phys. Rev. D, 2011, **83**: 034013
- 65 LI G. Eur. Phys. J. C, 2013, **73**: 2621
- 66 Brambilla N et al. (Quarkonium Working Group collaboration). hep-ph/0412158
- 67 Brambilla N, Pineda A, Soto J, Vairo A. Rev. Mod. Phys., 2005, **77**: 1423
- 68 WANG Q, Hanhart C, ZHAO Q. Phys. Lett. B, 2013, **725**: 106
- 69 Cleven M, WANG Q, GUO F K, Hanhart C, Meißner U G, ZHAO Q. arXiv:1310.2190 [hep-ph]
- 70 WU X G, Hanhart C, WANG Q, ZHAO Q. Phys. Rev. D, 2014, **89**: 054038
- 71 LI G, LIU X H. Phys. Rev. D, 2013, **88**: 094008
- 72 LI G, WANG W. Phys. Lett. B, 2014, **733**: 100
- 73 LI G, LIU X H, ZHOU Z. Phys. Rev. D, 2014, **90**: 054006
- 74 Lipkin H J. Nucl. Phys. B, 1987, **291**: 720
- 75 Lipkin H J. Phys. Lett. B, 1986, **179**: 278
- 76 Weinberg S. Phys. Rev., 1965, **137** B672
- 77 Baru V et al. Phys. Lett. B, 2004, **586**: 53
- 78 Casalbuoni R, Deandrea A, Bartolomeo N Di, Gatto R, Feruglio F, Nardulli G. Phys. Lett. B, 1992, **292**: 371
- 79 Casalbuoni R, Deandrea A, Bartolomeo N Di, Gatto R, Feruglio F, Nardulli G. Phys. Lett. B, 1993, **299**: 139
- 80 Burdman G, Donoghue J F. Phys. Lett. B, 1992, **280**: 287
- 81 YAN T M, CHENG H Y, CHEUNG C Y, LIN G L, LIN C Y, YU H L. Phys. Rev. D, 1992, **46**: 1148; 1997, **55**: 5851
- 82 Falk A F, Luke M E. Phys. Lett. B, 1992, **292**: 119
- 83 Casalbuoni R, Deandrea A, Bartolomeo N Di, Gatto R, Feruglio F, Nardulli G. Phys. Rept., 1997, **281**: 145
- 84 Isola C, Ladisa M, Nardulli G, Santorelli P. Phys. Rev. D, 2003, **68**: 114001
- 85 Deandrea A, Gatto R, Nardulli G, Polosa A D. JHEP, 1999, **9902**: 021
- 86 Locher M P, LU Y, ZOU B S. Z. Phys. A, 1994, **347**: 281
- 87 LI X Q, ZOU B S. Phys. Lett. B, 1997, **399**: 297
- 88 Cleven M, GUO F K, Hanhart C, Meißner U G. Eur. Phys. J. A, 2011, **47**: 120