Partial decay widths of $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ into $J/\psi p$ in a molecular scenario

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In the present work, we assign the newly observed $P_c^+(4312)$ as a $I(J^P) = \frac{1}{2}^-$ molecular state composed of $\Sigma D$, while $P_c^+(4440)$ and $P_c^+(4457)$ as $\Sigma D^*$ molecular states with $I(J^P) = \frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. In this molecular scenario, we investigate the $J/\psi p$ decay mode of these three states. We find that the partial widths are consistent with the reported total decay widths within uncertainties. Moreover, we predict the ratios of the partial decay width of the $J/\psi p$ mode for these three states, which could serve as a crucial test of the present molecular scenario.

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I. INTRODUCTION

In 2015, the LHCb collaboration reported two states, i.e., $P_c(4380)$ and $P_c(4450)$, in the $J/\psi p$ invariant mass spectrum of the $\Lambda_b \to J/\psi pK$ process [1], which stimulated great theoretical interests in understanding their nature. Since both states were observed in the $J/\psi p$ channel, thus their quark components are more likely to be $cc\bar{u}d\bar{a}$, which indicates their pentaquark nature. The QCD sum rule (QSR) study with diquark-diquark-antiquark type interpolating currents and some local hidden charm currents indicates that $P_c^+(4380)$ and $P_c^+(4450)$ could be pentaquark states with $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^+$, respectively [2, 3]. Such assignments were also supported by the diquark-triquark model with the quark configuration of both $P_c^+(4380)$ and $P_c^+(4450)$ being $[cu][udc]$ [4] and the diquark model [5], where $P_c^+(4380)$ and $P_c^+(4450)$ are pentaquark states in two separate octet multiplets of flavor SU(3). The study in the constitute quark model with the color-spin hyperfine potential indicated that $P_c^+(4380)$ could be a compact pentaquark [6], while $P_c^+(4450)$ could not be assigned as a pentaquark state in the color-flux-tube model with a five-body confinement potential [7]. In Ref. [8], by using a simple Gursey-Radici inspired mass formula, the authors argued that $P_c(4380)$ could be a compact pentaquark state in a group theory approach.

It should be noted that in the vicinity of the observed $P_c^+(4380)$ and $P_c^+(4450)$, there are abundant thresholds of a baryon and a meson, such as $\Sigma^0 D^{(*)}$, $\Lambda \bar{D}^*$, $\chi_{c1} p$, $\psi(2S)p$. Thus, it’s natural to investigate the observed $P_c$ states in a molecular scenario. The QSR studies indicated that $P_c^+(4380)$ could be assigned as a $\Sigma \bar{D}^*$ molecular state with $J^P = \frac{3}{2}^-$, and $P_c^+(4450)$ with $J^P = \frac{5}{2}^+$ generated from the coupled channel interactions of $\Sigma \bar{D}^*$ and $\Lambda \bar{D}^*$ [9, 10]. The investigations in both the chiral quark model [11] and quark delocalization color screening model [12] showed that $P_c^+(4380)$ could be a molecular state composed of $\Sigma \bar{D}$ with $J^P = \frac{3}{2}^-$, while the study in the latter model indicated that the $\Sigma \bar{D}$ states with $J^P = \frac{5}{2}^+$ should be a resonance, which could not correspond to the observed $P_c^+(4450)$. A full coupled channel analysis of $D^{(*)}\Lambda_c - D^{(*)}\Sigma(c)$ indicated that the $J^P$ quantum numbers of $P_c^+(4380)$ and $P_c^+(4450)$ could be $\frac{3}{2}^-$ and $\frac{5}{2}^+$, respectively [13]. In the one-pion-exchange model, both $P_c^+(4380)$ and $P_c^+(4450)$ could be assigned as molecular states composed of $\Sigma \bar{D}$ and $\Sigma \bar{D}^*$, respectively [14], while the authors in Ref. [15] concluded that the dominant component of $P_c^+(4380)$ should be $\Sigma \bar{D}$. Considering the potential resulted from pseudoscalar, vector and scalar meson exchanges, the study in a Bethe-Salpeter equation approach indicated that $P_c^+(4380)$ and $P_c^+(4450)$ should be $\Sigma \bar{D}$ and $\Sigma \bar{D}^*$ molecular states, respectively [16]. Besides the molecular state composed of an anti-charmed meson and a charmed baryon, in Ref. [17], the authors assigned $P_c^+(4380)$ as a $\psi(2S)n$ bound state with $J^P = \frac{3}{2}^-$ or $\frac{1}{2}^+$, while $\frac{5}{2}^+$. The kinematical effects of the rescattering from $\chi_{c1} p \to J/\psi p$ were believed to be compatible with $P_c^+(4450)$ [18–20].

As the pentaquark story rolls on, very recently, the LHCb Collaboration updated their analysis of the $\Lambda_b \to J/\psi pK$ pro-

| State  | Mass (MeV) | Width (MeV) | R(%) |
|-------|------------|-------------|------|
| $P_c^+(4312)$ | 4311.9 ± 0.7±0.6 | 9.8 ± 2.7 ± 3.3 | 0.30 ± 0.07±0.09 |
| $P_c^+(4440)$ | 4440.3 ± 1.3±1.1 | 20.6 ± 4.9± 6.7 | 1.11 ± 0.33±0.22 |
| $P_c^+(4457)$ | 4457.3 ± 0.6±0.5 | 6.4 ± 2.0±0.9 | 0.53 ± 0.16±0.14 |
process with 9 times larger data sample than the one in Ref. [1], more structure details in the \( J/\psi \rho \) invariant mass spectrum were exposed [21]. The structure \( P_1^c(4450) \) reported in Ref. [1] were found to be the superposition of two narrow states with a small mass gap, which are \( P_{c1}^0(4440) \) and \( P_{c2}^0(4457) \), while the very broad state \( P_{c2}^0(4438) \) was found to be insensitive to the data analysis [21]. Moreover, the updated analysis found an additional narrow structure near 4.3 GeV, named \( P_{c1}^0(4312) \) [21]. The parameters of the newly discovered states are listed in Table I. The thresholds in this mass range is \( \Sigma^+ D^0/\Sigma^+ D^- \) and \( \Sigma^+ D^0/\Sigma^+ D^- \), which are 4317.73/4323.55 and 4459.75/4464.23 MeV, respectively. Considering only \( S \) wave interactions, the \( J^P \) quantum numbers of these two system could be \( 1^+ \) and \( 1^+/2^- \), respectively. Moreover, the small mass gap of \( P_{c1}^0(4440) \) and \( P_{c2}^0(4457) \) indicates that these two states may have the same components and the mass gap comes from the spin-spin interactions of the components. Similar to the case of the interactions in the quark model, the masses of the states with paralleled spins are usually a bit larger than the ones with anti-paralleled spins, thus in the present work, we would assign \( P_{c1}^0(4440) \) and \( P_{c2}^0(4457) \) are \( \Sigma^+ D^0 \) molecular states with \( J^P = 1^+ \) and \( 1^+/2^- \), respectively, while \( P_{c1}^0(4312) \) as a \( \Sigma^+ D^0 \) molecule with \( J^P = 1^- \). Along this way, we investigate the decays, in particular the observe \( J/\psi \rho \) mode, of the newly observed \( P_c \) states, which could help us to further test the present molecular scenario.

This work is organized as follows. After introduction, we present the molecular structure of the pentaquark states and relevant formulae for the decay of \( P_c \to J/\psi \rho \) in an effective Lagrangian approach, and in Section III, the numerical results and discussions are presented. Section IV devotes to a short summary.

II. MOLECULAR STRUCTURES AND DECAYS OF THE \( P_c \) STATES

A. Molecular structures

In the present work, we use an effective Lagrangian approach to describe all the involved interactions at the hadronic level. The \( S \)-wave interactions between the molecular states and their components read as,

\[
\mathcal{L}_{P_c} = -ig_{P_c} P_{c1}(x) \int dy \left[ \sqrt{3} \phi^{++}(x + \omega \bar{D}' \Sigma y) D^-(x - \omega \bar{P} D y) + \sqrt{3} \phi^+(x + \omega \bar{D}' \Sigma y) D^0(x - \omega \bar{P} D y) \right] + \sqrt{3} \phi^+(x + \omega \bar{D}' \Sigma y) D^0(x - \omega \bar{P} D y) \right] + h.c. + \sqrt{3} \phi^+(x + \omega \bar{D}' \Sigma y) D^0(x - \omega \bar{P} D y) \right] + h.c. + \sqrt{3} \phi^+(x + \omega \bar{D}' \Sigma y) D^0(x - \omega \bar{P} D y) \right] + h.c. .
\]

where \( P_{c1}, P_{c2} \) and \( P_{c3} \) refer to \( P_1^c(4312), P_1^c(4440) \) and \( P_1^c(4457), \) respectively, and \( \omega_{ij} = m_i/(m_i + m_j) \) is a kinematical parameter with \( m_i \) being the mass of the molecular components. The correlation function \( \Phi(y^2) \) is introduced to describe the distributions of the components in the molecule, which depends only on the Jacobian coordinate \( y \). The Fourier transformation of the correlation functions is,

\[
\Phi(y^2) = \int \frac{d^4 p}{(2\pi)^4} e^{-ip \cdot y} \Phi(p^2).
\]

The introduced correlation function also plays the role of removing the ultraviolet divergences in Euclidean space, which requires that the Fourier transformation of the correlation function should drop fast enough in the ultraviolet region. Generally, the Fourier transformation of the correlation function is chosen in the Gaussian form [22–26],

\[
\Phi(-p^2) = \exp \left( \frac{-p^2}{\Lambda^2} \right),
\]

where \( p_E \) is the Euclidean momentum and \( \Lambda \) is the parameter which reflects the distribution of the components inside the molecular states.

The coupling constants between the hadronic molecule and its components can be determined by the compositeness condition [22–29]. For a spin-1/2 hadronic molecule, the compositeness condition is,

\[
Z \equiv 1 - \Sigma'(m) = 0,
\]

where \( \Sigma'(m) \) is the derivative of the mass operator (as shown in Fig. 1) of the hadronic molecule. As for the spin-3/2 particle, the mass operator can be divided into the transverse and longitudinal parts, i.e.,

\[
\Sigma^\mu\nu(m) = \delta^\mu\nu \Sigma^T(m) + \frac{p^\mu p^\nu}{p^2} \Sigma^L(m).
\]

And the compositeness condition for a spin-3/2 particle is,

\[
Z \equiv 1 - \Sigma^T'(m) = 0.
\]
where $\Sigma_T(m)$ is the derivative of the transverse part of the mass operator. The mass operator can be divided into the conventional transverse and longitudinal parts,

$$\Sigma^{\mu\nu}(m) = g^{\mu\nu}_T \Sigma_T(p) + \frac{p^\mu p^\nu}{p^2} \Sigma^L(m)$$  \hspace{1cm} (7)

Here, the explicit form of the mass operators of $P_{c1}$, $P_{c2}$ and $P_{c3}$ are,

$$\Sigma_{P_{c1}}(p) = g^2_{P_{c1}} \int \frac{d^4q}{(2\pi)^4} \frac{1}{(q - \omega_D^0)p} \frac{1}{q^2 - m^2_D}$$

$$\Sigma_{P_{c2}}(p) = g^2_{P_{c2}} \int \frac{d^4q}{(2\pi)^4} \frac{1}{(q - \omega_D^0)p} \frac{1}{q^2 - m^2_D}$$

$$\Sigma^{\mu\nu}_{P_{c3}}(p) = g^2_{P_{c3}} \int \frac{d^4q}{(2\pi)^4} \frac{1}{(q - \omega_D^0)p} \frac{1}{q^2 - m^2_D}$$

$$\times \frac{1}{(p - q)^2 - m^2_D},$$ \hspace{1cm} (8)

$$\times \frac{1}{(p - q)^2 - m^2_D},$$ \hspace{1cm} (9)

B. Decays of $P_{c3} \rightarrow J/\psi p$

Besides the effective Lagrangian presented in Eq. (1), we need additional Lagrangians related to $\Sigma D^{(\ast)}D^c$ and $\psi D^{(\ast)}D^c$ interactions, which are [30–34],

$$\mathcal{L}_{\Sigma D^{(c)}D^{(c)}} = -ig_{\Sigma D^{(c)}D^{(c)}}(\partial^\mu D^\nu - D^\nu \partial^\mu D^c)$$

$$+ g_{\Sigma D^{(c)}D^{(c)}} \partial^\mu \partial^\nu \partial^\mu \partial^\nu \partial^\mu \partial^\nu$$

$$+ g_{\Sigma D^{(c)}D^{(c)}}(\partial^\mu D^c - D^c \partial^\mu D^c),$$

$$\mathcal{L}_{\Sigma D^{(c)}D^{(c)}} = g_{\Sigma D^{(c)}D^{(c)}} \Sigma_{D^c} \Sigma_{D^c} - ig_{\Sigma D^{(c)}D^{(c)}} \Sigma_{D^c}.$$ \hspace{1cm} (10)

In the heavy quark limit, the couplings constants $g_{\Sigma D^cD^c}$ can be related to a universal gauge coupling $g_2$ by [30–33],

$$g_{\Sigma D^cD^c} = 2g_2 \sqrt{m_D m_{D^c}},$$

$$g_{\Sigma D^cD^c} = 2g_2 \sqrt{m_D m_{D^c}},$$

$$g_{\Sigma D^cD^c} = 2g_2 \sqrt{m_D m_{D^c}},$$ \hspace{1cm} (12)

with $g_2 = \sqrt{m_D/(2m_D^2 f_0^2)}$ and $f_0 = 426$ MeV is the decay constant of $J/\psi$, which can be estimated by the dilepton partial width of $J/\psi$ [35]. As for the coupling constants related to the baryons, we take the same values, i.e., $g_{\Sigma ND^c} = 3.9$ and $g_{\Sigma ND^c} = 2.69$, as those in Refs. [36, 37].

In the present hadronic molecular scenario, the diagrams contributing to the $P_{c} \rightarrow J/\psi p$ decay are presented in Fig. 2. In particular, for the $P_{c}(4312) \rightarrow J/\psi p$ decay, the amplitudes corresponding to Fig. 2-(a) -(b) are,

$$\mathcal{M}_u = (i)^3 \int \frac{d^4q}{(2\pi)^4} \Phi(-\omega_D p_1 - \omega_D p_2)$$

$$\times \left[ -ig_{\Sigma D^cD^c} \right] \frac{1}{\sqrt{m_D m_{D^c}}} \left[ -ig_{\Sigma D^cD^c} \right]$$

$$\times \left[ -ig_{\Sigma D^cD^c} \right] \frac{1}{\sqrt{m_D m_{D^c}}} \left[ -ig_{\Sigma D^cD^c} \right]$$ \hspace{1cm} (13)

$$\mathcal{M}_b = (i)^3 \int \frac{d^4q}{(2\pi)^4} \Phi(-\omega_D p_1 - \omega_D p_2)$$

$$\times \left[ g_{\Sigma ND^c} \right] \frac{1}{\sqrt{m_D m_{D^c}}} \left[ -ig_{\Sigma D^cD^c} \right]$$

$$\times \left[ g_{\Sigma ND^c} \right] \frac{1}{\sqrt{m_D m_{D^c}}} \left[ -ig_{\Sigma D^cD^c} \right]$$ \hspace{1cm} (14)

As for the $P_{c}(4440) \rightarrow J/\psi p$ process, the amplitudes corresponding to Fig. 2-(c)-(d) are,

$$\mathcal{M}_u = (i)^3 \int \frac{d^4q}{(2\pi)^4} \Phi(-\omega_D p_1 - \omega_D p_2)$$

$$\times \left[ -ig_{\Sigma D^cD^c} \right] \frac{1}{\sqrt{m_D m_{D^c}}} \left[ -ig_{\Sigma D^cD^c} \right]$$

$$\times \left[ -ig_{\Sigma D^cD^c} \right] \frac{1}{\sqrt{m_D m_{D^c}}} \left[ -ig_{\Sigma D^cD^c} \right]$$ \hspace{1cm} (15)
TABLE II: The coupling constants of $g_P$, defined in Eq. (1) and $\Gamma_P$, the partial decay widths of $P_c \rightarrow J/\psi p$ in units of MeV. For comparison, we also list the measured total width of the pentaquark states [21].

| $\Lambda$ (GeV) | $g_{p_1}$ | $g_{p_2}$ | $g_{p_3}$ | $\Gamma_{p_1}$ | $\Gamma_{p_2}$ | $\Gamma_{p_3}$ |
|----------------|-----------|-----------|-----------|---------------|---------------|---------------|
| 0.5            | 2.56      | 2.31      | 2.03      | 1.1           | 1.8           | 0.66          |
| 1.0            | 2.25      | 1.72      | 1.77      | 5.6           | 9.3           | 2.6           |
| 1.5            | 2.02      | 1.54      | 1.68      | 13.6          | 27.8          | 4.2           |
| Expt. [21]     | ...       | ...       | ...       | 9.8 ± 2.7 $^{+0.2}_{-0.4}$ | 20.6 ± 4.9$^{+0.1}_{-0.1}$ | 6.4 ± 2.0$^{+0.2}_{-0.2}$ |

$M_{d} = (i)^{3} \int \frac{d^{4}q}{(2\pi)^{4}} \Phi (-\omega_{D_{s}p_{1}}-\omega_{D_{p}-p_{2}}^{2})$

\[ \times \frac{1}{\beta_{1} - m_{1}} \left[ g_{p_{1}} y_{i}^{a_{i}} \left[ i g_{p_{1}} u_{p_{1}} \right] \right. \]

\[ \times \left[ (g_{p_{2}} y_{i}^{a_{i}}) \left[ i g_{p_{2}} u_{p_{2}} \right] \right] \]

\[ \times \left( -g_{\pi \tau} + p_{2} p_{2} / m_{D_{p}}^{2} - g_{\pi \mu} + g_{\pi \mu} / m_{D_{p}}^{2} \right) \]

\[ \frac{q^{2} - m_{D_{p}}^{2}}{p_{2}^{2} - m_{D_{p}}^{2}}. \]  

(16)

Since the components of $P_{c}^{*}(4440)$ and $P_{c}^{*}(4457)$ are exactly the same, the diagrams contributing to $P_{c}^{*}(4457) \rightarrow J/\psi p$ are the same as those of $P_{c}^{*}(4440) \rightarrow J/\psi p$ as shown in Fig. 2-(c)-(d). The corresponding amplitudes are

$M'_{d} = (i)^{3} \int \frac{d^{4}q}{(2\pi)^{4}} \Phi (-\omega_{D_{s}p_{1}} - \omega_{D_{p} - p_{2}}^{2})$

\[ \times \left[ -i g_{s_{N}} y_{i}^{a_{i}} \frac{1}{\beta_{1} - m_{1}} \right. \]

\[ \times \left[ ig_{p_{1}} u_{p_{1}} \right] \]

\[ \times \left[ (g_{p_{2}} y_{i}^{a_{i}}) e^{i(\vec{q}_{1}^{2} - \vec{q}_{2}^{2})} \right] \]

\[ \times \left( -g_{\pi \tau} + p_{2} p_{2} / m_{D_{p}}^{2} - g_{\pi \mu} + g_{\pi \mu} / m_{D_{p}}^{2} \right) \]

\[ \frac{q^{2} - m_{D_{p}}^{2}}{p_{2}^{2} - m_{D_{p}}^{2}}. \]  

(17)

With the above amplitudes, we can compute the partial decay width of $P_{c} \rightarrow J/\psi p$ by,

\[ \Gamma_{P_{c}} \rightarrow \frac{1}{2J + 1} \frac{1}{18\pi} \frac{1}{m_{0}^{2}} |M|^{2}. \]  

(19)

III. NUMERICAL RESULTS AND DISCUSSION

Before we discuss the partial decay widths of $P_{c} \rightarrow J/\psi p$, we need to determine the coupling constants related to the molecular state and its components. By using the compositeness condition of the molecular states, we can estimate the coupling constants, which depend on the model parameter $\Lambda$. The value of the model parameter $\Lambda$ usually depends on the particular process under consideration and is of order of 1 GeV [22–26]. In the present work, both $D$ and $D^{*}$ are $S$-wave charmed mesons and in the heavy quark limit, they are degenerated states, thus, we take the same model parameter for $P_{c}^{*}(4312), P_{c}^{*}(4440)$ and $P_{c}^{*}(4457)$. In Table II, we present the coupling constants with several typical $\Lambda$ values. We find that the values of the coupling constants for the three $P_{c}$ states are very close, which reflects the similarity of these molecular states. Moreover, the $\Lambda$ dependences of the coupling constants are similar, which decrease with increasing $\Lambda$.

The computed partial decay widths of $P_{c} \rightarrow J/\psi p$ are presented in Table II. Our study indicates that the partial widths of $P_{c} \rightarrow J/\psi p$ increase with increasing $\Lambda$. In particular, the partial decay width of $P_{c} \rightarrow J/\psi p$ is 13.6, 27.8 and 4.2 MeV for $P_{c}^{*}(4312), P_{c}^{*}(4440)$ and $P_{c}^{*}(4457)$ with $\Lambda = 1.5$ GeV, which are consistent with the total width of $P_{c}^{*}(4312), P_{c}^{*}(4440)$ and $P_{c}^{*}(4457)$ within uncertainties. At present, the branching ratio of $P_{c} \rightarrow J/\psi p$ are not reported yet, thus the magnitudes of the partial widths should not be compared with the total width directly. However, we find the $\Lambda$ dependences of the partial width for $P_{c} \rightarrow J/\psi p$ process are very similar, thus, one can further compute the ratio of the partial width of the $J/\psi p$ mode for the three molecular states, which should be weakly dependent on the model parameter. Here, we define three ratios, which are $R_{23} = \Gamma_{p_{2}} / \Gamma_{p_{3}}, R_{21} = \Gamma_{p_{2}} / \Gamma_{p_{1}}, R_{31} = \Gamma_{p_{3}} / \Gamma_{p_{1}}$. Based on the computed decaywidths, these three ratios are estimated to be,

\[ R_{23} = 2.7 \sim 6.6, R_{21} = 1.6 \sim 2.0, R_{31} = 0.3 \sim 0.6, \]  

(20)

which could be tested in future precise measurements by LHCb.

In addition, LHCb Collaboration has measured the production ratio as listed in Table I. With the estimated ratio in Eq. (20), one can roughly obtain the ratios of the $\Lambda_{b} \rightarrow P_{c}K$. Similarly, we define $R_{23} = \mathcal{B}(\Lambda_{b} \rightarrow P_{c}^{*}(4440)K)/\mathcal{B}(\Lambda_{b} \rightarrow P_{c}^{*}(4457)K), R_{21} = \mathcal{B}(\Lambda_{b} \rightarrow P_{c}^{*}(4440)K)/\mathcal{B}(\Lambda_{b} \rightarrow P_{c}^{*}(4312)K)$ and $R_{31} = \mathcal{B}(\Lambda_{b} \rightarrow P_{c}^{*}(4457)K)/\mathcal{B}(\Lambda_{b} \rightarrow P_{c}^{*}(4312)K)$. Taking $\Lambda = 1.0$ GeV as an example, with the center values of the width and production ratio, the ratios $R_{23}, R_{21}$ and $R_{31}$ are estimated to be 1.83, 3.38 and 1.85, respectively. These ratios could also serve as a test of the molecular scenario.

IV. SUMMARY

Inspired by the recent measurement of three pentaquark states in the $J/\psi p$ invariant mass spectrum of the $\Lambda_{b} \rightarrow J/\psi pK$ process and noting that the newly observed states are
very close to the thresholds of $\Sigma_0D$ and $\Sigma_0D^*$, we assume that the newly observed state $P^+_c(4312)$ is a $J(P^0) = \frac{1}{2}(-\frac{1}{2})$ molecular state composed of $\Sigma_0D$, while $P^+_c(4440)$ and $P^+_c(4457)$ are $\Sigma_0D^*$ molecular states with $J(P^0) = \frac{1}{2}(-\frac{1}{2})$ and $J(P^0) = \frac{1}{2}(\frac{1}{2})$, respectively. In this scenario, the small mass gap of $P^+_c(4440)$ and $P^+_c(4457)$ originates from the spin-spin interaction of the components.

In this molecular scenario, we investigate the decay process $P_c \rightarrow J/\psi p$, which is the observed decay mode of $P_c$. Our study indicated that the partial widths of the considered process increase with the increase of the modell parameter, when we set $\Lambda = 1.5$ GeV, the so-obtained partial widths are consistent with the corresponding total widths within uncertainties. Moreover, we estimated the ratio of the partial width of $P_c \rightarrow J/\psi p$ for the newly observed exotic states, and we find that these ratios are weakly dependent on the modell parameter, thus the predictions of these ratios should be more reliable, which could serve as a crucial test of the molecular scenario.

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Note added: We noticed several papers in the arXiv related to this topic when this manuscript was close to completion. By using QSR, the authors in Ref. [38] extended their previous study of molecular state composed of anti-charmed mesons and charmed baryons and found that the newly observed pentaquark states could be molecular states. The studies in the one-boson-exchange models [39, 40] and contact range effective field theory [41] indicated that $P^+_c(4312)$ could be assigned as a $J(P^0) = \frac{1}{2}(-\frac{1}{2})$ molecular state composed of $\Sigma_0D$, while $P^+_c(4440)$ and $P^+_c(4457)$ could be $\Sigma_0D^*$ molecular state with $J(P^0) = \frac{1}{2}(-\frac{1}{2})$ and $\frac{1}{2}(\frac{1}{2})$, respectively, which is the same as the assignments in the present work. Note that in Ref. [41], the assignment of $P_c(4440)$ having spin-parity $1/2^-$ and $P_c(4440)$ having $3/2^-$ is also likely. In Ref. [42], the authors indicated that the isospin breaking decay process of the $P_c(4457)$, such as $P_{3/2} \rightarrow J/\psi\Delta$, could be used to check the $\Sigma_0D^*$ molecular picture of the $P^+_c(4457)$.

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