

Exploring the molecular scenario of $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$

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In the present work, we assign the newly observed $P_c(4312)$ as a $I(J^P) = \frac{1}{2}(\frac{1}{2})^-$ molecular state composed of $\Sigma_c \bar{D}$, while $P_c(4440)$ and $P_c(4457)$ as $\Sigma_c \bar{D}^*$ molecular states with $I(J^P) = \frac{1}{2}(\frac{1}{2})^-$ and $\frac{1}{2}(\frac{3}{2})^-$, respectively. In this molecular scenario, we investigate the $P_c \rightarrow J/\psi p$ process of these three states and further predict the ratios of the $\mathcal{B}(P_c \rightarrow J/\psi p)$ and those of $\mathcal{B}(\Lambda_b \rightarrow P_c K)$ between these three states, which could serve as a crucial test of the present molecular scenario.

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I. INTRODUCTION

Very recently, the LHCb Collaboration reported a new narrow state $P_c(4312)$ and a two-peak structure of $P_c(4450)$ through analyzing the data of the $\Lambda_b \rightarrow J/\psi p K$ process that was collected in run I and run II [1,2]. The significance of the new $P_c(4312)$ state is 7.3σ and that of the two-peak structure, which corresponding to the $P_c(4440)$ and $P_c(4457)$, is 5.4σ . The resonance parameters of three P_c states are

$$\begin{aligned} (m, \Gamma)_{P_c(4312)} &= (4311.9 \pm 0.7_{-0.6}^{+6.8}, 9.8 \pm 2.7_{-4.5}^{+3.7}) \text{ MeV}, \\ (m, \Gamma)_{P_c(4440)} &= (4440.3 \pm 1.3_{-4.7}^{+4.1}, 20.6 \pm 4.9_{-10.1}^{+8.7}) \text{ MeV}, \\ (m, \Gamma)_{P_c(4457)} &= (4457.3 \pm 0.6_{-1.7}^{+4.1}, 6.4 \pm 2.0_{-1.9}^{+5.7}) \text{ MeV}. \end{aligned} \quad (1)$$

In addition, the LHCb Collaboration measured the ratio $R = \mathcal{B}(\Lambda_b \rightarrow P_c K) \times \mathcal{B}(P_c \rightarrow J/\psi p) / \mathcal{B}(\Lambda_b \rightarrow J/\psi p K)$, which are

$$\begin{aligned} R_{P_c(4312)} &= (0.30 \pm 0.07_{-0.09}^{+0.34})\%, \\ R_{P_c(4440)} &= (1.11 \pm 0.33_{-0.10}^{+0.22})\%, \\ R_{P_c(4457)} &= (0.53 \pm 0.16_{-0.13}^{+0.15})\%, \end{aligned} \quad (2)$$

respectively.

This new observation is similar to but different from the analysis in 2015, where two pentaquark states, $P_c(4380)$ and $P_c(4450)$ were first reported in the $\Lambda_b \rightarrow J/\psi p K$ process [3–5]. Due to a 9 times larger sample of $\Lambda_b \rightarrow J/\psi p K$ than the one used in 2015, the experimentalist can nowadays perform a better analysis. The structure $P_c(4450)$ reported in Ref. [3] was found to be a superposition of two narrow states with a small mass gap, which are $P_c(4440)$ and $P_c(4457)$, while the very broad state $P_c(4380)$ was found to be insensitive to the analysis [1]. and an additional narrow structure near 4.3 GeV, named $P_c(4312)$ was observed [1].

The P_c states were observed in the $J/\psi p$ channel, and thus, their quark components are more likely to be $c\bar{c}uud$, which indicates their pentaquark nature. Actually, before the observation of $P_c(4380)$ and $P_c(4450)$, there were some predictions of the hidden-charm pentaquark states [6–9]. Stimulated by the observation of the hidden-charm pentaquark states in 2015, theorists investigated the nature of the two pentaquark states from different aspects, such as the baryon-meson molecule [10–20], the compact pentaquark state [21–33], and the kinematical effect [34–36]. The studies of the $P_c(4380)$ and $P_c(4450)$ were well reviewed in Refs. [37–44].

As the pentaquark story rolls on, the new result of the P_c states immediately attracted the attentions of theorists.

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The authors in Refs. [45–47] explained the new observed P_c states as compact pentaquark states in the diquark model, where the quark and diquark are the fundamental units. The analysis from the constituent quark model [48,49] also supported the compact pentaquark interpretations to the new P_c states. Based on the experimental observations, the photoproductions of the three P_c states were predicted in Refs. [50,51]. In addition, in the vicinity of the observed P_c masses, there are abundant charmed meson and charmed baryon thresholds; thus, these three new observed P_c states could be interpreted as hadronic molecules. Within the molecular scenario, the mass spectrum [52–65] and the decay properties [62–65] were investigated by various methods.

Along the way of the molecular scenario, one can find the thresholds in the mass range of new P_c states are $\Sigma_c^+ \bar{D}^0 / \Sigma_c^{++} D^-$ and $\Sigma_c^+ \bar{D}^{*0} / \Sigma_c^{++} D^{*-}$, which are 4317.73/4323.55 and 4459.75/4464.23 MeV, respectively. The mass difference between the $\Sigma_c^+ \bar{D}^0$ threshold and $P_c(4312)$ is 5.73 MeV. While the gap between the $\Sigma_c^+ \bar{D}^{*0}$ threshold and $P_c(4440)/P_c(4457)$ is 19.75/2.75 MeV, which indicates the new P_c states could be good candidates of $\Sigma_c D^{(*)}$ molecular states, the investigations in Refs. [53–65] supports such an assignment. Considering only S wave interactions, $P_c(4312)$ can be assigned as an $\Sigma_c \bar{D}$ molecular state with $J^P = \frac{1}{2}^-$, while $P_c(4440)$ and $P_c(4457)$ can be $\Sigma_c \bar{D}^*$ molecular states with $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$, respectively. In this molecular

assignment, the small mass gap of $P_c(4440)$ and $P_c(4457)$ can result 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 parallel spins are usually a bit larger than the ones with antiparallel spins. However, more efforts are needed to check such assignment. We notice that the LHCb Collaboration measured the ratios of the production fractions as shown in Eq. (2), which provides us an opportunity to evaluate the hadronic molecule interpretations via their decay properties, in particular, we focus on the $J/\psi p$ mode, which is the only observed one.

This work is organized as follows. After the Introduction, we present the molecular structure of the pentaquark states and relevant formulas for the decay of $P_c \rightarrow J/\psi p$ in an effective Lagrangian approach, and in Sec. III, the numerical results and discussions are presented. Section IV is devoted 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

$$\begin{aligned}
\mathcal{L}_{P_c} = & -ig_{P_{c1}} \bar{P}_{c1}(x) \int dy \left[\sqrt{\frac{2}{3}} \Sigma_c^{++}(x + \omega_{\bar{D}\Sigma_c} y) D^-(x - \omega_{\Sigma_c \bar{D}} y) + \sqrt{\frac{1}{3}} \Sigma_c^+(x + \omega_{\bar{D}\Sigma_c} y) \bar{D}^0(x - \omega_{\Sigma_c \bar{D}} y) \right] \Phi(y^2) + \text{H.c.} \\
& + g_{P_{c2}} \bar{P}_{c2}(x) \gamma^\mu \gamma^5 \int dy \left[\sqrt{\frac{2}{3}} \Sigma_c^{++}(x + \omega_{\bar{D}^* \Sigma_c} y) D_\mu^{*-}(x - \omega_{\Sigma_c \bar{D}^*} y) + \sqrt{\frac{1}{3}} \Sigma_c^+(x + \omega_{\bar{D}^* \Sigma_c} y) \bar{D}_\mu^{*0}(x - \omega_{\Sigma_c \bar{D}^*} y) \right] \Phi(y^2) \\
& + \text{H.c.} \\
& - ig_{P_{c3}} \bar{P}_{c3}^\mu(x) \int dy \left[\sqrt{\frac{2}{3}} \Sigma_c^{++}(x + \omega_{\bar{D}^* \Sigma_c} y) D_\mu^{*-}(x - \omega_{\Sigma_c \bar{D}^*} y) + \sqrt{\frac{1}{3}} \Sigma_c^+(x + \omega_{\bar{D}^* \Sigma_c} y) \bar{D}_\mu^{*0}(x - \omega_{\Sigma_c \bar{D}^*} y) \right] \Phi(y^2) + \text{H.c.},
\end{aligned} \tag{3}$$

where P_{c1} , P_{c2} , and P_{c3} refer to $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$, 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

$$\Phi(y^2) = \int \frac{d^4 p}{(2\pi)^4} e^{-ipy} \tilde{\Phi}(-p^2). \tag{4}$$

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 [66–70],

$$\tilde{\Phi}(-p^2) = \text{Exp}\left(\frac{-p_E^2}{\Lambda^2}\right), \tag{5}$$

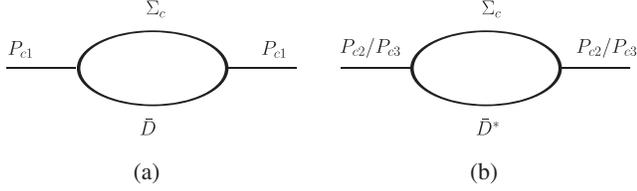


FIG. 1. The mass operators of the P_{c1} [diagram (a)] and P_{c2}/P_{c3} [diagram (b)], where P_{c1} is assigned as a $\Sigma_c \bar{D}$ hadronic molecule with $J^P = \frac{1}{2}^-$, while P_{c2} and P_{c3} are $\Sigma_c \bar{D}^*$ hadronic molecules with $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively.

where p_E is the Euclidean momentum and Λ 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 [66–73]. For a spin-1/2 hadronic molecule, the compositeness condition is

$$Z \equiv 1 - \Sigma'(m) = 0, \quad (6)$$

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.,

$$\Sigma^{\mu\nu}(m) = g_{\perp}^{\mu\nu} \Sigma^T(m) + \frac{p^\mu p^\nu}{p^2} \Sigma^L(m). \quad (7)$$

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

$$Z \equiv 1 - \Sigma^{Tl}(m) = 0, \quad (8)$$

where $\Sigma^{Tl}(m)$ is the derivative of the transverse part of the mass operator.

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

$$\begin{aligned} \Sigma_{P_{c1}}(p) &= g_{P_{c1}}^2 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}^2(q - \omega_{\Sigma \bar{D}} p) \frac{1}{\not{q} - m_{\Sigma_c}} \\ &\times \frac{1}{(p - q)^2 - m_{\bar{D}}^2}, \end{aligned} \quad (9)$$

$$\begin{aligned} \Sigma_{P_{c2}}(p) &= g_{P_{c2}}^2 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}^2(q - \omega_{\Sigma \bar{D}^*} p) \gamma^5 \gamma^\mu \frac{1}{\not{q} - m_{\Sigma_c}} \gamma^\mu \gamma^5 \\ &\times \frac{-g^{\mu\nu} + (p - q)^\mu (p - q)^\nu / m_{\bar{D}^*}^2}{(p - q)^2 - m_{\bar{D}^*}^2}, \end{aligned} \quad (10)$$

$$\begin{aligned} \Sigma_{P_{c3}}^{\mu\nu}(p) &= g_{P_{c3}}^2 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}^2(q - \omega_{\Sigma \bar{D}^*} p) \frac{1}{\not{q} - m_{\Sigma_c}} \\ &\times \frac{-g^{\mu\nu} + (p - q)^\mu (p - q)^\nu / m_{\bar{D}^*}^2}{(p - q)^2 - m_{\bar{D}^*}^2}. \end{aligned} \quad (11)$$

B. Decays of $P'_{cs} \rightarrow J/\psi p$

Besides the effective Lagrangian presented in Eq. (3), we need additional Lagrangians related to $\Sigma_c D^{(*)} P$ and $\psi D^{(*)} D^{(*)}$ interactions, which are [74–78],

$$\begin{aligned} \mathcal{L}_{\psi D^{(*)} D^{(*)}} &= -i g_{\psi D D} \bar{\psi}_\mu (\partial^\mu D D^\dagger - D \partial^\mu D^\dagger) \\ &+ g_{\psi D^* D} \epsilon^{\mu\nu\alpha\beta} \partial_\mu \bar{\psi}_\nu (D_\alpha^* \overleftrightarrow{\partial}_\beta D^\dagger - D \overleftrightarrow{\partial}_\beta D_\alpha^{*\dagger}) \\ &+ i g_{\psi D^* D^*} \bar{\psi}^\mu (D_\nu^* \overleftrightarrow{\partial}^\nu D_\mu^{*\dagger} \\ &+ D_\mu^* \overleftrightarrow{\partial}^\nu D_\nu^{*\dagger} - D_\nu^* \overleftrightarrow{\partial}_\mu D^{*\nu\dagger}), \\ \mathcal{L}_{\Sigma_c N D^{(*)}} &= g_{\Sigma_c N D^*} \bar{N} \gamma_\mu \vec{\tau} \cdot \vec{\Sigma}_c D^{*\mu} - i g_{\Sigma_c N D} \bar{N} \gamma_5 \vec{\tau} \cdot \vec{\Sigma}_c D. \end{aligned} \quad (12)$$

In the heavy quark limit, the couplings constants $g_{\psi D^{(*)} D^{(*)}}$ can be related to a universal gauge coupling g_2 by [74–77],

$$\begin{aligned} g_{\psi D D} &= 2g_2 \sqrt{m_\psi} m_D, \\ g_{\psi D^* D} &= 2g_2 \sqrt{m_\psi m_{D^*} / m_D}, \\ g_{\psi D^* D^*} &= 2g_2 \sqrt{m_\psi} m_{D^*}, \end{aligned} \quad (13)$$

with $g_2 = \sqrt{m_\psi} / (2m_D f_\psi)$ and $f_\psi = 426$ MeV is the decay constant of J/ψ , which can be estimated by the dilepton partial width of J/ψ [79]. As for the coupling constants related to the baryons, we take the same values, i.e., $g_{\Sigma_c N D^*} = 3.0$ and $g_{\Sigma_c N D} = 2.69$, as those in Refs. [80,81].

In the present hadronic molecular scenario, the diagrams contributing to the $P_c \rightarrow J/\psi p$ decay are presented in

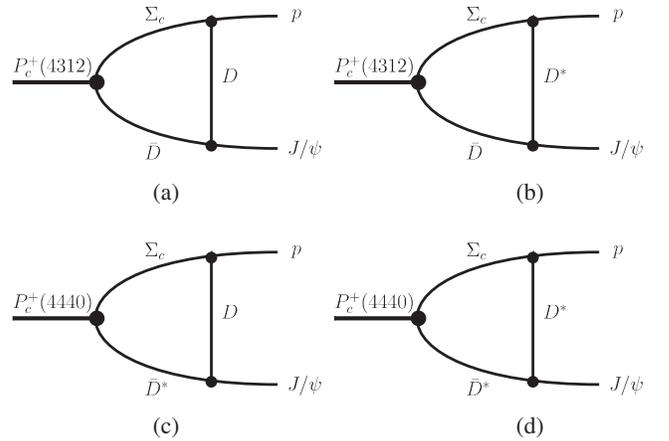


FIG. 2. Feynman diagrams contributing to processes $P_c(4312) \rightarrow J/\psi p$ [diagrams (a)–(b)] and $P_c(4440) \rightarrow J/\psi p$ [diagrams (c)–(d)], while the diagrams related to $P_c(4457) \rightarrow J/\psi p$ are the same as those of $P_c(4440) \rightarrow J/\psi p$, since the hadron components of $P_c(4440)$ and $P_c(4457)$ are exactly the same in the present scenario.

Fig. 2. In particular, for the $P_c(4312) \rightarrow J/\psi p$ decay, the amplitudes corresponding to Figs. 2(a)–2(b) are

$$\begin{aligned} \mathcal{M}_a &= (i)^3 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}(-(\omega_{\bar{D}\Sigma_c} p_1 - \omega_{\Sigma_c \bar{D}} p_2)^2) \\ &\quad \times [-ig_{\Sigma_c ND} \bar{u}_p \gamma^5] \frac{1}{\not{p}_1 - m_1} [-ig_{P_{c1}} u_{P_c}] \\ &\quad \times [-ig_{\psi DD} \epsilon_\psi^\mu (-iq^\mu + ip_2^\mu)] \frac{1}{p_2^2 - m_D^2} \frac{1}{q^2 - m_D^2}, \end{aligned} \quad (14)$$

$$\begin{aligned} \mathcal{M}_b &= (i)^3 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}(-(\omega_{\bar{D}\Sigma_c} p_1 - \omega_{\Sigma_c \bar{D}} p_2)^2) \\ &\quad \times [g_{\Sigma_c ND^*} \bar{u}_p \gamma_\mu] \frac{1}{\not{p}_1 - m_1} [-ig_{P_{c1}} u_{P_c}] \\ &\quad \times [g_{\psi D^* D} \epsilon^{\mu\nu\alpha\beta} (ip_4^\mu) \epsilon_\psi^\nu (-ip_2^\beta + iq^\beta)] \\ &\quad \times \frac{1}{p_2^2 - m_{D^*}^2} \frac{-g_{\alpha\phi} + q_\alpha q_\phi / m_{D^*}^2}{q^2 - m_{D^*}^2}. \end{aligned} \quad (15)$$

As for the $P_c(4440) \rightarrow J/\psi p$ process, the amplitudes corresponding to Figs. 2(c)–2(d) are

$$\begin{aligned} \mathcal{M}_c &= (i)^3 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}(-(\omega_{\bar{D}^* \Sigma_c} p_1 - \omega_{\Sigma_c \bar{D}^*} p_2)^2) \\ &\quad \times [-ig_{\Sigma_c ND} \bar{u}_p \gamma^5] \frac{1}{\not{p}_1 - m_1} [g_{P_{c2}} \gamma^\phi \gamma^5 u_{P_c}] \\ &\quad \times [g_{\psi D^* D} \epsilon_{\mu\nu\alpha\beta} (ip_4^\mu) \epsilon_\psi^\nu (ip_2^\beta - iq^\beta)] \\ &\quad \times \frac{-g_{\phi\alpha} + p_{2\phi} p_{2\alpha} / m_{D^*}^2}{p_2^2 - m_{D^*}^2} \frac{1}{q^2 - m_D^2}, \end{aligned} \quad (16)$$

$$\begin{aligned} \mathcal{M}_d &= (i)^3 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}(-(\omega_{\bar{D}^* \Sigma_c} p_1 - \omega_{\Sigma_c \bar{D}^*} p_2)^2) \\ &\quad \times [g_{\Sigma_c ND^*} \bar{u}_p \gamma_\mu] \frac{1}{\not{p}_1 - m_1} [g_{P_c} \gamma^\phi \gamma^5 u_{P_c}] \\ &\quad \times \{ig_{\psi D^* D^*} [g^{\alpha\tau} (iq^\tau - ip_2^\tau) + g^{\alpha\eta} (iq^\tau - ip_2^\tau) - g^{\tau\eta}] \\ &\quad \times (iq^\alpha - ip_2^\alpha)\} \frac{-g_{\nu\tau} + p_{2\nu} p_{2\tau} / m_{D^*}^2}{p_2^2 - m_{D^*}^2} \\ &\quad \times \frac{-g_{\eta\mu} + q_\eta q_\mu / m_{D^*}^2}{q^2 - m_{D^*}^2}. \end{aligned} \quad (17)$$

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 Figs. 2(c)–2(d). The corresponding amplitudes are

$$\begin{aligned} \mathcal{M}'_c &= (i)^3 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}(-(\omega_{\bar{D}^* \Sigma_c} p_1 - \omega_{\Sigma_c \bar{D}^*} p_2)^2) \\ &\quad \times [-ig_{\Sigma_c ND} \bar{u}_p \gamma^5] \frac{1}{\not{p}_1 - m_1} [-ig_{P_{c3}} u_{P_c}^\phi] \\ &\quad \times [g_{\psi D^* D} (ip_4^\mu) \epsilon_\psi^\nu (ip_2^\beta - iq^\beta)] \\ &\quad \times \frac{-g_{\phi\alpha} + p_{2\phi} p_{2\alpha} / m_{D^*}^2}{p_2^2 - m_{D^*}^2} \frac{1}{q^2 - m_D^2}, \end{aligned} \quad (18)$$

$$\begin{aligned} \mathcal{M}'_d &= (i)^3 \int \frac{d^4 q}{(2\pi)^4} \tilde{\Phi}(-(\omega_{\bar{D}^* \Sigma_c} p_1 - \omega_{\Sigma_c \bar{D}^*} p_2)^2) \\ &\quad \times [g_{\Sigma_c ND^*} \bar{u}_p \gamma_\mu] \frac{1}{\not{p}_1 - m_1} [-ig_{P_{c3}} u_{P_c}^\nu] \{ig_{\psi D^* D^*} \epsilon_\psi^\alpha \\ &\quad \times [g^{\alpha\tau} (iq^\tau - ip_2^\tau) + g^{\alpha\eta} (iq^\tau - ip_2^\tau) - g^{\tau\eta}] \\ &\quad \times (iq^\alpha - ip_2^\alpha)\} \frac{-g_{\nu\tau} + p_{2\nu} p_{2\tau} / m_{D^*}^2}{p_2^2 - m_{D^*}^2} \\ &\quad \times \frac{-g_{\eta\mu} + q_\eta q_\mu / m_{D^*}^2}{q^2 - m_{D^*}^2}. \end{aligned} \quad (19)$$

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

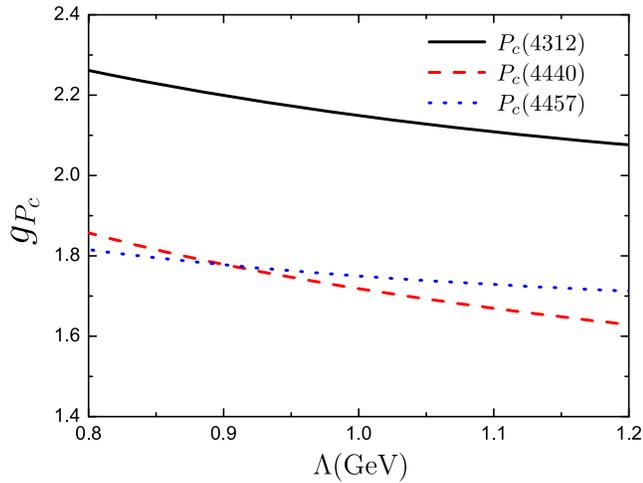
$$\Gamma_{P_c} = \frac{1}{2J+1} \frac{1}{8\pi} \frac{|\vec{p}|^2}{m_0^2} |\bar{\mathcal{M}}|^2, \quad (20)$$

where the J is the angular momentum of the P_c states and \vec{p} is the 3-momentum of the final states.

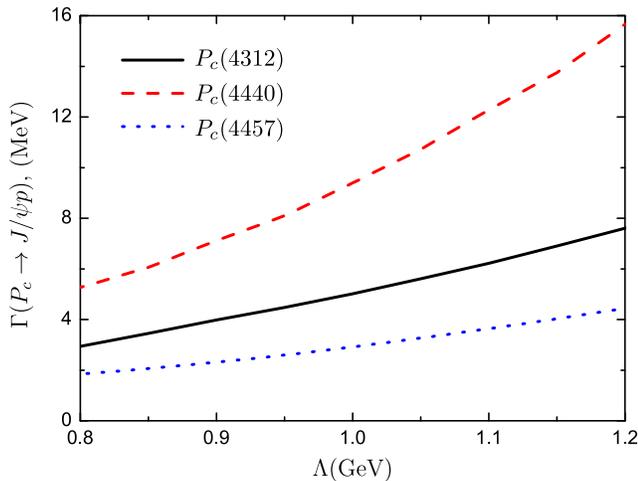
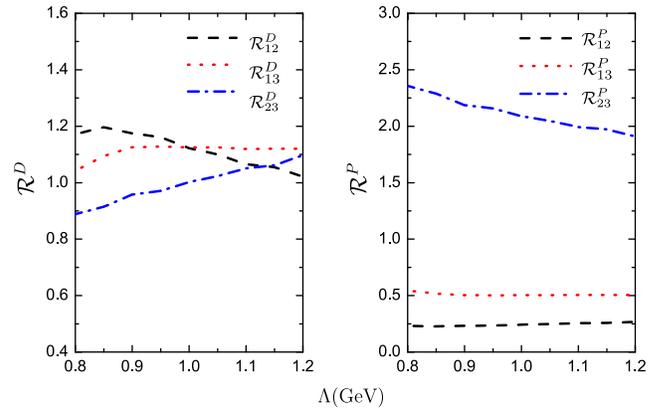
III. NUMERICAL RESULTS AND DISCUSSION

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 g_{P_c} depending on the model parameter Λ , which is of the order 1 GeV [66–69]. However, the accurate value of Λ cannot be determined by the first principle. Alternatively, it is usually determined by the measured decay width. Unfortunately, the present experimental data are still too few to determine the Λ for $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$. Thus, in the present work, we vary Λ from 0.8 to 1.2 GeV to check the Λ dependence of our results.

In Fig. 3, the Λ dependence of the coupling constants are presented. We find that the values of the coupling constants for three P_c states are very similar, especially for $P_c(4440)$ and $P_c(4457)$, which reflects the similarity of these molecular states. Moreover, the Λ dependence of the coupling constants are similar, in particular, the coupling constants decrease with the increasing of Λ .


 FIG. 3. The coupling constant g_{P_c} depending on the parameter Λ .

The estimated partial widths of $P_c \rightarrow J/\psi p$ depending on Λ are presented in Fig. 4, where the partial widths of $P_c \rightarrow J/\psi p$ increase with the increasing of Λ . On the one hand, our estimated results of the partial decay widths do not exceed the upper limit of the observed width, which indicates the chosen range of Λ is reasonable. On the other hand, one may find that the estimated partial decay widths are sensitive to the Λ . Although the rough range of Λ is determined, the accurate value of partial decay width can not be well predicted. Nevertheless, the $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ are considered as the molecular states composed of $\Sigma_c D^{(*)}$ in the present work. Both the D and D^* are S -wave charmed mesons, and they are degenerate states in the heavy quark limit. The model parameter for $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ can be the same due to such similarities. Here, we define the decay ratios as


 FIG. 4. The partial decay widths of $J/\psi p$ mode of $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$, which depend on the parameter Λ .

 FIG. 5. The numerical results of decay ratios \mathcal{R}^D in Eq. (21) (left) and production ratios in Eq. (22) (right), which depend on the parameter Λ .

$$\begin{aligned} \mathcal{R}_{12}^D &= \mathcal{B}(P_c(4312) \rightarrow J/\psi p) / \mathcal{B}(P_c(4440) \rightarrow J/\psi p), \\ \mathcal{R}_{13}^D &= \mathcal{B}(P_c(4312) \rightarrow J/\psi p) / \mathcal{B}(P_c(4457) \rightarrow J/\psi p), \\ \mathcal{R}_{23}^D &= \mathcal{B}(P_c(4440) \rightarrow J/\psi p) / \mathcal{B}(P_c(4457) \rightarrow J/\psi p). \end{aligned} \quad (21)$$

The numerical results of the decay ratios \mathcal{R}^D are presented in Fig. 5 (left panel), which weakly depend on the parameter Λ . In the Λ range considered, in particular, \mathcal{R}_{12}^D , \mathcal{R}_{13}^D , and \mathcal{R}_{23}^D are predicted to be 1.17–1.02, 1.04–1.12, and 0.89–1.10, where the central values of the observed widths were adapted in the present estimation. Since the LHCb Collaboration has measured the $R = \mathcal{B}(\Lambda_b \rightarrow P_c K) \times \mathcal{B}(P_c \rightarrow J/\psi p) / \mathcal{B}(\Lambda_b \rightarrow J/\psi p K)$ as listed in Eq. (2), we can further calculate the production ratios as

$$\begin{aligned} \mathcal{R}_{12}^P &= \mathcal{B}(\Lambda_b \rightarrow P_c(4312)K) / \mathcal{B}(\Lambda_b \rightarrow P_c(4440)K), \\ \mathcal{R}_{13}^P &= \mathcal{B}(\Lambda_b \rightarrow P_c(4312)K) / \mathcal{B}(\Lambda_b \rightarrow P_c(4457)K), \\ \mathcal{R}_{23}^P &= \mathcal{B}(\Lambda_b \rightarrow P_c(4440)K) / \mathcal{B}(\Lambda_b \rightarrow P_c(4457)K). \end{aligned} \quad (22)$$

The numerical results are presented in Fig. 5 (right panel). In the considered Λ range, \mathcal{R}_{12}^P , \mathcal{R}_{13}^P , and \mathcal{R}_{23}^P are predicted to be 0.23–0.26, 0.54–0.50, and 2.36–1.91. These predicted ratios in Eqs. (21)–(22) weakly depend on the model parameter, which could serve as a crucial 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 $\Lambda_b \rightarrow J/\psi p K$ process and noting that the newly observed states are very close to the thresholds of $\Sigma_c \bar{D}$ and $\Sigma_c \bar{D}^*$, we assume that the newly observed state $P_c(4312)$ is a $I(J^P) = \frac{1}{2}(1^-)$ molecular state composed of $\Sigma_c \bar{D}$, while $P_c(4440)$ and $P_c(4457)$ are $\Sigma_c \bar{D}^*$ molecular states with

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ and $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$, 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 the present molecular scenario, we investigate the decays of $P_c \rightarrow J/\psi p$ since $J/\psi p$ mode is the only observed decay pattern of P_c states. Our estimations indicate the partial widths are dependent on Λ . Moreover, we present a reliable prediction for the decay ratios \mathcal{R}_{12}^D , \mathcal{R}_{13}^D , and \mathcal{R}_{23}^D , which are weakly dependent on the model parameter. Together with the experimental measured product of production fraction, we can estimate production ratios \mathcal{R}_{12}^P , \mathcal{R}_{13}^P , and \mathcal{R}_{23}^P , which are also weakly dependent on the model parameter.

Nowadays, the LHCb Collaboration have accumulated a large data sample of $\Lambda_b \rightarrow J/\psi p K$, which makes it possible to measure the decay ratios and the production ratios with high precision. In addition, the photoproduction process, $\gamma p \rightarrow J/\psi p$, is a good source to produce the P_c states. The related experiments have been carried out at Jefferson Lab [82,83], and the GlueX Collaboration

recently reported the first measurement of the near-threshold $J/\psi p$ exclusive photoproduction off the proton [84], in which the upper limits on the individual branching ratios were reported. Eventually with more data, the branching ratios of $P_c \rightarrow J/\psi p$ for individual P_c states could be measured, which could further test our predictions in the present work.

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