Pion-induced production of hidden-charm pentaquarks $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$

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The production of the hidden-charm pentaquarks $P_c$ via pion-induced reaction on a proton target is investigated within an effective Lagrangian approach. Three experimentally observed states, $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$, are considered in the calculation, and the Reggeized $t$-channel meson exchange is considered as main background for the reaction $\pi^+ p \rightarrow J/\psi n$. The numerical results show that the experimental data of the total cross section of the reaction $\pi^+ p \rightarrow J/\psi n$ at $W \approx 5$ GeV can be well explained by contribution of the Reggeized $t$ channel with reasonable cutoff. If the branching ratios $Br[P_c \rightarrow J/\psi N] \approx 3\%$ and $Br[P_c \rightarrow \pi N] \approx 0.05\%$ are taken, the average value of the cross section from the $P_c(4312)$ contribution is about 1.2 nb/100 MeV, which is consistent with existing rude data at near-threshold energies. The results indicate that the differential cross sections from the $P_c$ states are relatively flat. High-precision experimental measurements on the reaction $\pi^+ p \rightarrow J/\psi n$ at near-threshold energies are suggested to confirm the LHCb hidden-charm pentaquarks as genuine states, and such experiments are also helpful to understand the origin of these resonance structures.

PACS numbers: 11.10.Ef, 12.40.Nn, 14.20.Lq

I. INTRODUCTION

Study of the exotic hadrons beyond the constituent quark model is an important way to understand how quarks combine to form a hadron. As of now, many hidden-charm exotic states have been observed and listed in the Review of Particle Physics (PDG) [1]. Different from the charmonium-like states, only three possible candidates for the hidden-charm pentaquarks were reported in the literature [2]. The studies of the hidden-charm pentaquarks in both experiment and theory are very important to understand the exotic hadrons.

The observation of two possible candidates of hidden-charm pentaquarks, $P_c(4450)$ and $P_c(4380)$, was reported by the LHCb Collaboration in 2015 [3], which is an important progress of the search for the exotic hadrons. Recently, LHCb updated their results of the hidden-charm pentaquark [2]. The $P_c(4450)$ splits into two narrower structure with masses of $4440.3 \pm 1.3^{+4.1}_{-0.7}$ MeV and $4457.3 \pm 0.6^{+1.7}_{-0.6}$ MeV, which are renamed as $P_c(4440)$ and $P_c(4457)$, respectively. An additional state $P_c(4312)$ with a mass of $4311.9 \pm 0.7^{+0.8}_{-0.6}$ MeV was also reported. After the result was released, the theoretical researches on these three $P_c$ states is springing up [4–23].

In fact, after the observation in 2015, many theoretical interpretations of these structures were proposed [24–30]. The $P_c(4450)$ and $P_c(4380)$ are close to the $\Sigma_c D^*$ and $\Sigma_c D$ thresholds. It is very natural to assign them as two molecular states of $\Sigma_c D^*$ and $\Sigma_c D$, respectively [29, 31]. However, the opposite parities of these two states make it difficult to assign both states as S-wave molecular states. The new LHCb results show that the previous $P_c(4450)$ structure should be composed of two peaks of the $P_c(4440)$ and $P_c(4457)$. It is reasonable to expect that puzzling spin parities are from the low precision of previous observation and will be changed with more data accumulated. Combined with the observation of the $P_c(4312)$ which is close to the $\Sigma_c D$ threshold, these three states can be naturally interpreted as the S-wave molecular states. There are only two S-wave $\Sigma_c D^*$ state with spin parities $1/2^-$ and $3/2^-$, and only one S-wave $\Sigma_c D$ state with $1/2^-$. In fact, before the LHCb observation of the $P_c$ states, there have been many predictions of the hidden-charm pentaquarks [32–34], the calculations in which support the existence of such bound states. It is interesting to see that two states $P_c(4440)$ and $P_c(4457)$ were observed near $\Sigma_c D^*$ threshold and one state $P_c(4312)$ was observed near $\Sigma_c D$ threshold. It was further supported by the theoretical studies after the new LHCb results released [4, 6–8, 10, 13], that is, the $P_c(4312)$ can be assigned as a S-wave $\Sigma_c D^*$ bound state with spin parity $1/2^-$, and the $P_c(4440)$ and $P_c(4457)$ as S-wave $\Sigma_c D^*$ bound states with spin parities $1/2^-$ and $3/2^-$, respectively.

Although the molecular-state interpretation is quite consistent with the current LHCb observation, there are still many other proposals to understand the origin of these $P_c$ states [4–23]. Moreover, up to now, these hidden-charm pentaquarks were still only observed in the $\Lambda_b$ decay at LHCb. If these states is really composed of a charm quark pair and three light quark, it should be easy to be produced by striking a nucleon by a particle, such as nucleon, photon or pion, to excite a charm quark pair in the nucleon. Confirmation of the existence of these resonance structure in the photon- or pion-induced production is very important to establish the $P_c$ states as genuine particles. Hence, it is urgent to search for the hidden-charm pentaquark in such production processes.
The productions of the hidden-charm pentaquarks with nucleon target are proposed even before the LHCb’s first observation of the hidden-charm pentaquarks $P_c(4450)$ and $P_c(4380)$. In Ref. [35] the hidden-charm pentaquark states were predicted and suggested to be looked for in the reaction $p\bar{p} \rightarrow p\bar{p} J/\psi$. In Ref. [38], the photoproduction of the hidden-charm pentaquark was first suggested to be applied at Jefferson Laboratory. Then, the productions of these predicted pentaquark state via pion- or kaon-induced reaction were calculated [36, 37]. After the states $P_c(4450)$ and $P_c(4380)$ were experimentally observed, many theoretical calculations about these two pentaquarks produced in different processes appeared [39–44]. After new LHCb results was released, we also updated the predictions about the photoproductions of three $P_c$ states [45], which is accessible at JLab.

Another important way to study the hidden-charm pentaquarks is pion-induced production [36, 39]. At present, there are some experimental data for the $\pi^- p \rightarrow J/\psi n$ reaction [46, 47]. Furthermore, we note that $P_c(4312), P_c(4440)$ and $P_c(4457)$ are all observed on the $J/\psi p$ invariant mass spectrum. In terms of experiments, the secondary pion beam is accessible at J-PARC [48, 49] and COMPASS [50] with high intensity. Therefore, combining these experimental data to examine the role of these three states in pion–-induced reaction is very necessary. The reaction mechanisms of the reaction $\pi^- p \rightarrow J/\psi n$ are illustrated in Fig. 1. These include the production of pentaquark $P_c$ states via s- and u-channel (as shown in Fig. 1 (a)–(b)), and t-channel $\pi$ and $\rho$ exchanges as depicted in Fig. 1 (c). Considering the off-shell effect of the intermediate $P_c$ states, the contribution from u-channel will be omitted.

![Feynman diagrams](image)

**FIG. 1.** (Color online) Feynman diagrams for the $\pi^- p \rightarrow J/\psi n$ reaction.

In this work, within the frame of an effective Lagrangian approach, the productions of $P_c$ states via pion-induced reaction on a proton target will be investigated. In the calculation, three hidden-charm pentaquarks, $P_c(4457), P_c(4440)$, and $P_c(4312)$, which are assumed to carry spin parities $3/2^-, 1/2^-$, and $1/2^-$, respectively, will be considered in the calculation. The Reggeized treatment will be applied to t channel to describe the main background of the productions.

This paper is organized as follows. After the Introduction, we present the formalism including Lagrangians and amplitudes of the $P_c$ states productions in Section II. The numerical results of the cross section follow in Section III. Finally, the paper ends with a brief summary.

## II. FORMALISM

### A. Lagrangians

To gauge the contributions of Fig. 1, one needs the following Lagrangians for the s-channel $P_c$ exchanges [36, 37, 51–53].

\[
L_{\pi P_c}^{1/2} = \frac{g_{\pi P_c}^{1/2}}{m_\pi} \bar{\Psi} \cdot A P_c + H.c.,
\]

\[
L_{\rho P_c}^{1/2} = \frac{g_{\rho P_c}^{1/2}}{m_\rho} \bar{\Psi} \gamma_5 \gamma_\mu P_c \rho^\mu + H.c.,
\]

\[
L_{n P_c}^{3/2} = \frac{g_{n P_c}^{3/2}}{m_N} \bar{\Psi} \gamma_5 \gamma_\mu \gamma_5 \gamma_\nu P_c \rho_{\mu\nu} + H.c.,
\]

\[
L_{P_c,Ar}^{3/2} = \frac{-ig_{P_c,Ar}^{3/2}}{2m_N} \bar{\Psi} \gamma_\mu \gamma_5 \gamma_\nu P_c \rho_{\mu\nu} - \frac{g_{P_c,Ar}^{3/2}}{2m_N} \bar{\Psi} \gamma_\mu \gamma_5 \gamma_\nu P_c \rho_{\mu\nu} + H.c.,
\]

where $N, \pi, P_c$ and $\psi$ are the nucleon, the pion, the $P_c$ state and the $J/\psi$ meson fields, respectively, and $\tau$ is the Pauli matrix. The values of $g_{\pi P_c}^{1/2}$, and $g_{\rho P_c}^{1/2}$ can be determined by the corresponding decay widths,

\[
\Gamma_{P_c,\pi N}^{1/2} = \frac{3g_{\pi P_c N}^{1/2}}{4\pi m_P} \left| \bar{\psi}_N \right|^2,
\]

\[
\Gamma_{P_c,\pi N}^{3/2} = \frac{g_{\pi P_c N}^{3/2}}{4\pi m_P^2} \left| \bar{\psi}_N \right|^3,
\]

with

\[
\left| \bar{\psi}_N \right|^2 = \frac{\lambda(m_P^2, m_N^2, m_{\pi N}^2)}{2m_P},
\]

\[
E_{\pi N} = \sqrt{\left| \bar{\psi}_N \right|^2 + m_{\pi N}^2},
\]

where $\lambda$ is the Källen function with a definition of $\lambda(x, y, z) = \sqrt{(x - y - z)^2 - 4yz}$. For the values of $g_{\pi P_c N}^{1/2}$ and $g_{\pi P_c N}^{3/2}$, we have conducted relevant research discussions in our previous studies about the photoproduction of the $P_c$ states [45]. Obviously, the coupling constants of the $g_{\pi P_c N}^{1/2}$ and $g_{P_c,Ar}^{3/2}$ are proportional to the corresponding values of decay width of $P_c$ states. In Table I, we present the values of coupling constants by assuming the $J/\psi N$ and $\pi N$ channels account for 3% and 0.05% of total widths of the $P_c$ states, respectively.

|               | $P_c(4312)$ | $P_c(4440)$ | $P_c(4457)$ |
|---------------|------------|------------|------------|
| $g_{\pi P_c N}$ | 0.06       | 0.08       | 0.036      |
| $g_{P_c,Ar}$   | 0.0036     | 0.0053     | 0.0005     |
For the $t$-channel via $\pi$ and $\rho$ exchanges, the effective Lagrangians read as

$$L_{\phi\pi} = -ig_{\rho\pi}(\pi^* \partial_\mu \pi^* - \partial_\mu \pi^* \pi^*)\psi^\mu,$$

$$L_{\phi\rho} = \frac{g_{\rho\phi}}{m_\rho} e^{\mu\nu} \partial_\mu \psi_\nu \partial_\rho F_{\mu\nu} \cdot \pi,$$

$$L_{\pi NN} = -ig_{\rho\pi} \bar{N} \gamma_5 \tau^i \cdot \not\! N,$$

$$L_{\rho NN} = -g_{\rho\pi} \bar{N} \gamma_\mu \left( \beta_\mu - \frac{\kappa_{\rho NN}}{2m_N} \sigma_{\mu\nu} \partial^\nu \right) \cdot \rho^\mu N,$$

where $N$, $\pi$, $\rho$, and $\psi$ are the nucleon, the pion, the $\rho$, and the $J/\psi$ meson fields, respectively. Here, the $g_{\rho\pi}/4\pi = 12.96$, $g_{\rho\phi} = 3.36$, and $\kappa_{\rho NN} = 0.1$ are adopted [40, 54, 55]. Moreover, The $g_{\rho\pi} = 8.2 \times 10^{-4}$ and $g_{\rho\phi} = 3.2 \times 10^{-2}$ will be used in the calculations, which was mentioned in Refs. [40, 56].

### B. Amplitudes

According to above Lagrangians, the scattering amplitude of the reaction $\pi^- p \rightarrow J/\psi n$ can be written as

$$-iM = g_{\rho\phi}(k_2)\bar{u}(p_2)\mathcal{A}_\rho u(p_1),$$

where $g_{\rho\phi}$ is the polarization vector of the $J/\psi$ meson, and $u$ is the Dirac spinor of the nucleon.

The reduced amplitudes $\mathcal{A}_\rho$ for the $s$ channel with each $J^P$ assignment of $P_c$ state and the $t$-channel are written as

$$\mathcal{A}_t^{\rho, (1/2^-)} = \sqrt{2} g_{\rho\phi} 2^{1/2^-} g_{\rho\phi} \hat{f}(q^2) \gamma_5 p_T \left( \frac{q^2 + m_P^2}{s - m_P^2 + im_P} \right) \Delta_{\rho(1/2^-)}(\hat{s}) \hat{y}_5,$$

$$\mathcal{A}_t^{\rho, (3/2^-)} = \sqrt{2} g_{\rho\phi} 2^{3/2^-} g_{\rho\phi} \hat{f}(q^2) \gamma_5 p_T \left( \frac{q^2 + m_P^2}{s - m_P^2 + im_P} \right) \Delta_{\rho(3/2^-)}(\hat{s}) \hat{y}_5,$$

$$\mathcal{A}_s = \sqrt{2} g_{\rho\phi} 2^{1/2^-} g_{\rho\phi} \hat{f}(q^2) \left( \frac{q^2 + m_P^2}{s - m_P^2 + im_P} \right) \Delta_{\rho(1/2^-)}(\hat{s}) \hat{y}_5,$$

where $\Delta_{\rho(1/2^-)} = -g_{\rho\phi} + \frac{1}{3} q^\mu q^\nu \gamma^\mu \gamma^\nu + \frac{1}{3m_P^2} (q^\mu q^\nu - q^\nu q^\mu) + \frac{2}{3m_P^2} q^\mu q^\nu,$

$$\hat{y}^\mu = i \left( g^\mu + q^\mu q^\nu/m_P^2 \right),$$

with $s = (k_1 + k_2)^2$ and $t = (k_1 - k_2)^2$ is the Mandelstam variables. For the $s$-channel $P_c$-state exchange, a general form factor is adopted to describe the size of hadrons, i.e. [43, 57],

$$\hat{f}(q^2) = \frac{\Lambda_t^4}{\Lambda_t^4 + (q^2 - m_P^2)^2},$$

where $q$, and $m_P$ are 4-momentum and mass of the exchanged $P_c$ state, respectively. Considering that it is a heavier hadron production, the typical value of cut off $\Lambda_t = 0.5$ GeV will be taken as used in Refs. [43, 51].

For the $t$-channel meson exchanges [37, 40, 57–62], the general form factor $\mathcal{F}(q^2)$ consisting of $\mathcal{F}_{\phi\pi} = (\Lambda_t^2 - m_t^2)/(\Lambda_t^2 - q^2)$ and $\mathcal{F}_{\rho NN} = (\Lambda_t^2 - m_{P_c}^2)/(\Lambda_t^2 - q^2)$ are taken into account. Here, $q^2$ and $m_P$ are 4-momentum and mass of the exchanged meson, respectively. The value of the cutoff $\Lambda_t$ will be discussed in the next section.

### C. Reggeized $t$-channel

The Reggeized treatment is often adopted to analyze hadron production at high energies[37, 57, 59–64]. It can be introduced by replacing the $t$-channel Feynman propagator by the Regge propagator as,

$$\frac{1}{t - m_P^2} \rightarrow \left( \frac{s}{s_{scale}} \right)^{\alpha_s(t)} \frac{\pi \alpha_s}{\Gamma[1 + \alpha_s(t)] \sin[\pi \alpha_s(t)]},$$

$$\frac{1}{t - m_P^2} \rightarrow \left( \frac{s}{s_{scale}} \right)^{\alpha_s(t)-1} \frac{\pi \alpha_s}{\Gamma[\alpha_s(t)] \sin[\pi \alpha_s(t)]},$$

where the scale factor $s_{scale}$ is fixed at 1 GeV. Moreover, the Regge trajectories of $\alpha_s(t)$ and $\alpha_s(t)$ read as [39, 58, 61],

$$\alpha_s(t) = 0.7(t - m_P^2), \quad \alpha_s(t) = 0.55 + 0.8t.$$  

One can observe that no additional parameter is introduced after the Reggeized treatment is introduced.

### III. NUMERICAL RESULTS

After above preparation, the cross section of the reaction $\pi^- p \rightarrow J/\psi n$ can be calculated and compared with experimental data [46, 47]. The differential cross section in the center of mass (c.m.) frame is written as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s} \left( \frac{k_{c.m.}^2}{k_{c.m.}^2} \right) \left( \frac{1}{2} \sum_j |M_j|^2 \right),$$

where $s = (k_1 + p_1)^2$, and $\theta$ denotes the angle of the outgoing $J/\psi$ meson relative to the $\pi$ beam direction in the c.m. frame. $k_{c.m.}^2$ and $k_{c.m.}^2$ are the three-momenta of the initial $\pi$ beam and final $J/\psi$, respectively.

In this work, total and differential cross sections of the reaction $\pi^- p \rightarrow J/\psi n$ are calculated as presented in Figs. 2–4. The total cross section of the reaction $\pi^- p \rightarrow J/\psi n$ is well matched by the cross section of $t$-channel by taking a cutoff $\Lambda_t = 2$ GeV. However,
at the same time, the data point near the threshold is more than an order of magnitude larger than the theoretical value of $t$-channel contribution. If we consider the contribution from the $s$-channel $P_c$ state, the data point near the threshold can be well explained. As shown in Fig. 2, one find that experimental data point near the threshold is consistent with the contribution from the $P_c(4312)$ state by assuming branching ratios $Br[P_c \rightarrow J/\psi N] \approx 3\%$ and $Br[P_c \rightarrow \pi N] \approx 0.05\%$. Due to adoption of the Regge propagator, we find that the cross section of the $t$ channel reaches a maximum at $W \approx 5$ GeV, and the total cross section decreases as the energy increases. If the Feynman propagator is adopted, the total cross section from $t$ channel would become larger and larger with the increase of the c.m. energy. The difference between the Regge model and the Feynman model will help to clarify the role of Regge propagator in the future experiment.

In order to distinguish the contributions from the three $P_c$ states more clearly, the Fig. 3 is presented, which is the same as the Fig. 2 except that the energy range is reduced. From Fig. 3, one can see three distinct peaks, which are from the contributions of three $P_c$ states. As we discussed in our previous work about the photoproduction of the $P_c$ states,[45], the $P_c(4312)$ can be observed within a bin of 0.1 GeV. But if one wants to distinguish two peaks from the $P_c(4440)$ and $P_c(4457)$, a bin at least at an order of 10 MeV is required. According to our calculation by assuming the branching ratios $Br[P_c \rightarrow J/\psi N] \approx 3\%$ and $Br[P_c \rightarrow \pi N] \approx 0.05\%$, if the width of a bin is 0.1 GeV, the theoretical average value of the cross section from the $P_c(4312)$ contribution is about 1.2 nb in a bin interval, which is just in agreement with the experimental value near the threshold.

In Fig. 4, we present our prediction of the differential cross section of the reaction $\pi^- p \rightarrow J/\psi n$ at different c.m. energy. It can be seen that the differential cross section has a large contribution at forward angles, which is caused by the Reggeized $t$-channel. In addition, we find that the shape of differential cross section tends to be flat at the c.m. energy $W = 4.312$, 4.44 and 4.457 GeV, which is due to the large contributions of the $P_c$ states at these energy points. Since the spin-parity quantum numbers of these $P_c$ states are selected to be $1/2^+$ or $3/2^-$, these $P_c$ states can couple to both the initial $\pi N$ and final $J/\psi N$ states.

FIG. 2. (Color online) Total cross section for the reaction $\pi^- p \rightarrow J/\psi n$. The black dashed, dark yellow dotted, green dot-dashed, blue dash-double-dotted, and red solid lines are for the background, the $P_c(4312)$, the $P_c(4440)$, the $P_c(4457)$ and total contributions, respectively. The bands stand for the error bar of the cutoff $\Lambda_c$. The experimental data are from Refs.[46, 47].

FIG. 3. (Color online) Same as Fig. 2 except that the energy range is reduced.

FIG. 4. (Color online) The differential cross section $d\sigma/d\cos\theta$ of the $\pi^- p \rightarrow J/\psi n$ process as a function of $\cos\theta$ at different c.m. energies. The black dashed, dark yellow dotted, green dot-dashed, blue dash-double-dotted, and red solid lines are for the background, $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ and total contributions, respectively.
in S wave, and the couplings by higher partial waves can be ignored because the momentum between the final $J/\psi N$ is very small. Therefore, the shape of the differential cross section of these $P_c$ states is relatively flat, which reflects the characteristics of the S-wave coupling.

IV. SUMMARY AND DISCUSSION

We have studied the reaction $\pi^- p \rightarrow J/\psi n$ within the Regge model. The numerical results show that the experimental data near the threshold can be well explained if we consider the contribution from the pentaquark states. In addition, numerical results also indicate the experimental data at $W \approx 5$ GeV is unlikely to come from the contribution of the $P_c$ states. Therefore, we suggest that experiments with high precision are needed because the momentum between the final $J/\psi N$ is very important.

At present, the branching ratios of $P_c$ decay to $J/\psi N$ and $\pi N$ are still undetermined, but if the branching ratios $BR[P_c \rightarrow J/\psi N]$ $\approx 3\%$ and $BR[P_c \rightarrow \pi N]$ $\approx 0.05\%$ are taken, then the average value of the cross section from the $P_c(4312)$ contribution is about $1.2$ nb/100 MeV, which coincides with the experimental data point near the threshold. Combined with the results in our previous article about the photoproduction of the $P_c$ states, it is reasonable to think that the branching ratios of $P_c$ states to $J/\psi N$ and $\pi N$ should be relatively small. Therefore, we suggest that experiments with high precision near the threshold can be performed, which is very important for determining the branch ratios and the internal structure of the $P_c$ states.

The differential cross sections for the reaction $\pi^- p \rightarrow J/\psi n$ are also calculated. One notices that the Reggeized $t$ channel is very sensitive to the $\theta$ angle and gives considerable contributions at forward angles. On the contrary, the shape of cross section from the $P_c$ states contribution is relatively flat, and it is related to the spin-parity quantum numbers of these $P_c$ states, which can be checked by future experiment and may be an effective way to examine the validity of the Reggeized treatment and spin parities of these $P_c$ states.

J-PARC and COMPASS can generate pion beam covering the above energy regions, and provide high-precision experimental data. Our theoretical results will provide valuable reference information for the studies of the pentaquark states at these facilities.

V. ACKNOWLEDGMENTS

This project is supported by the National Natural Science Foundation of China under Grants No. 11705076 and No. 11675228. We acknowledge the Natural Science Foundation of Gansu province under Grant No. 17JR5RA113. This work is partly supported by the HongLiu Support Funds for Excellent Youth Talents of Lanzhou University of Technology.

[1] M. Tanabashi et al. [ParticleDataGroup], “Review of Particle Physics,” Phys. Rev. D 98, 030001 (2018).
[2] R. Aaij et al. [LHCb Collaboration], “Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$,” arXiv:1904.03947 [hep-ex].
[3] R. Aaij et al. [LHCb Collaboration], “Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^* p$ Decays,” Phys. Rev. Lett. 115, 072001 (2015).
[4] R. Chen, Z. F. Sun, X. Liu and S. L. Zhu, “Strong LHCb evidence supporting the existence of the hidden-charm molecular pentaquarks,” arXiv:1903.11013 [hep-ph].
[5] H. X. Chen, W. Chen and S. L. Zhu, “Possible interpretations of the $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$,” arXiv:1903.11001 [hep-ph].
[6] M. Z. Liu, Y. W. Pan, F. Z. Peng, M. Sánchez Sánchez, L. S. Geng, A. Hosaka and M. Pavon Valderrama, “Emergence of a complete heavy-quark spin multiplet: seven molecular pentaquarks in light of the latest LHCb analysis,” arXiv:1903.11560 [hep-ph].
[7] J. He, “Study of $P_c(4457)$, $P_c(4440)$, and $P_c(4312)$ in a quasipotential Bethe-Salpeter equation approach,” Eur. Phys. J. C 79, 393 (2019).
[8] H. Huang, J. He and J. Ping, “Looking for the hidden-charm pentaquark resonances in $J/\psi p$ scattering,” arXiv:1904.00221 [hep-ph].
[9] A. Ali and A. Y. Parkhomenko, “Interpretation of the narrow $J/\psi p$ Peaks in $\Lambda_c \rightarrow J/\psi p K^-$ decay in the compact diquark model,” Phys. Lett. B 793, 365 (2019).
[10] C. J. Xiao, Y. Huang, Y. B. Dong, L. S. Geng and D. Y. Chen, “Partial decay widths of $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ into $J/\psi p$ in a molecular scenario,” arXiv:1904.00872 [hep-ph].
[11] Y. Shimizu, Y. Yamaguchi and M. Harada, “Heavy quark spin multiplet structure of $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$,” arXiv:1904.00587 [hep-ph].
[12] Z. H. Guo and J. A. Oller, “Anatomy of the newly observed hidden-charm pentaquark states: $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$,” Phys. Lett. B 793, 144 (2019).
[13] C. W. Xiao, J. Nieves and E. Oset, “Heavy quark spin symmetric molecular states from $D^0\Sigma_c^0$ and other coupled channels in the light of the recent LHCb pentaquarks,” arXiv:1904.01296 [hep-ph].
[14] F. K. Guo, H. J. Jing, U. G. Meiner and S. Sakai, “Isospin breaking decays as a diagnosis of the hadronic molecular structure of the $P_c(4457)$,” Phys. Rev. D 99, 091501 (2019).
[15] X. Cao and J. p. Dai, “Pentaquark photoproduction confronting with new LHCb observation,” arXiv:1904.06015 [hep-ph].
[16] H. Mutuk, “Neural Network Study of Hidden-Charm Pentaquark Resonances,” arXiv:1904.09756 [hep-ph].
[17] X. Z. Weng, X. L. Chen, W. Z. Deng and S. L. Zhu, “Hidden-charm pentaquarks and $P_c$ states,” arXiv:1904.09891 [hep-ph].
[18] R. Zhu, X. Liu, H. Huang and C. F. Qiao, “Implications of the hidden charm pentaquarks $P_c(X)$ at the LHCb,” arXiv:1904.10285 [hep-ph].
[19] J. R. Zhang, “Exploring a $\Sigma_c D$ state: with focus on $P_c(4312)^+$,” arXiv:1904.10711 [hep-ph].
[20] M. I. Eides, V. Y. Petrov and M. V. Polyakov, “New LHCb pentaquarks as hadrocharmonium states,” arXiv:1904.11616 [hep-ph].
[21] Z. G. Wang, “Analysis of the $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ and related hidden-charm pentaquark states with QCD sum rules,”
S. H. Kim, H. C. Kim and A. Hosaka, “Heavy pentaquark states,” arXiv:1905.04113 [hep-ph].

J. B. Cheng and Y. R. Liu, “$P_c(4457)$, $P_c(4440)$, and $P_c(4312)$: molecules or compact pentaquarks?,” arXiv:1905.08605 [hep-ph].

R. Chen, X. Liu, X. Q. Li and S. L. Zhu, “Identifying exotic hidden-pentaquark states,” Phys. Rev. Lett. 115, 132002 (2015).

H. X. Chen, W. Chen, X. Liu, T. G. Steele and S. L. Zhu, “Towards exotic hidden-charm pentaquarks in QCD,” Phys. Rev. Lett. 115, 172001 (2015).

L. Roca, J. Nieves and E. Oset, “LHCb pentaquark as a $D^*\Sigma_c \to D^*\Sigma_c$ molecular state,” Phys. Rev. D 92, 094003 (2015).

P. F. Guo, U. G. Meiner, W. Wang and Z. Yang, “How to reveal the exotic nature of the $P_c(4450)$,” Phys. Rev. D 92, 071502 (2015).

L. Maiani, A. D. Polosa and V. Riquer, “The New Pentaquarks in the Diquark Model,” Phys. Lett. B 749, 289 (2015).

J. He, “$D\Sigma_c$ and $D^*\Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks,” Phys. Lett. B 753, 547 (2016).

X. H. Liu, Q. Wang and Q. Zhao, “Understanding the newly observed heavy pentaquark candidates,” Phys. Lett. B 757, 231 (2016).

J. He, “Understanding spin parity of $P_c(4450)$ and $P_c(4274)$ in a hadronic molecular state picture,” Phys. Rev. D 95, 074004 (2017).

W. L. Wang, F. Huang, Z. Y. Zhang and B. S. Zou, “$\Sigma_c, \Sigma_c, D$ and $\Lambda_c, D$ states in a chiral quark model,” Phys. Rev. C 84 (2011) 015203 [arXiv:1101.4543 [nucl-th]].

Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, “The possible hidden charm-molecular baryons composed of anti-charmed meson and charmed baryon,” Chin. Phys. C 36, 6 (2012) [arXiv:1105.2901 [hep-ph]].

J. J. Wu, T.-S. H. Lee and B. S. Zou, “Nucleon Resonances with Hidden Charm in Coupled-Channel Models,” Phys. Rev. C 85 (2012) 044002 [arXiv:1202.1036 [nucl-th]].

J. J. Wu, R. Molina, E. Oset and B. S. Zou, “Prediction of narrow $N^*$ and $\Lambda^*$ resonances with hidden charm above 4 GeV,” Phys. Rev. Lett. 105, 232001 (2010).

X. Y. Wang and X. R. Chen, “The production of hidden charm baryon $N_c(4261)$ from $\pi^+\pi^+\eta_n$ reaction,” EPL 109, 41001 (2015).

X. Y. Wang and X. R. Chen, “Production of the superheavy baryon $\Lambda_{3c}^*(4209)$ in kaon-induced reaction,” Eur. Phys. J. A 51, 85 (2015).

Y. Huang, J. He, H. F. Zhang and X. R. Chen, “Discovery potential of hidden charm baryon resonances via photoproduction,” J. Phys. G 41, no. 11, 115004 (2014).

S. H. Kim, H. C. Kim and A. Hosaka, “Heavy pentaquark states $P_c(4380)$ and $P_c(4450)$ in the $J/\psi$ production induced by pion beams off the nucleon,” Phys. Lett. B 763, 358 (2016).

Q. F. Lü, X. Y. Wang, J. J. Xie, X. R. Chen and Y. B. Dong, “Neutral hidden charm pentaquark states $P_c^0(4380)$ and $P_c^+(4450)$ in $\pi^+\pi^+\eta_n$ reaction,” Phys. Rev. D 93, 034009 (2016).

E. J. Garzon and J. J. Xie, “Effects of a $N_c^0$ resonance with hidden charm in the $\pi^+\pi^+\eta_n$ reaction near threshold,” Phys. Rev. C 92, 035201 (2015).

M. Karlener and J. L. Rosner, “Photoproduction of Exotic Baryon Resonances,” Phys. Lett. B 752, 329 (2016).

Q. Wang, X. H. Liu and Q. Zhao, “Photoproduction of hidden charm pentaquark states $P_c^0(4380)$ and $P_c^+(4450)$,” Phys. Rev. D 92, 034022 (2015).

Z. E. Meziani et al., “A Search for the LHCb Charmed ’Pentaquark’ using Photo-Production of $J/\psi$ at Threshold in Hall C at Jefferson Lab,” arXiv:1609.00676 [hep-ex].

X. Y. Wang, X. R. Chen and J. He, “Possibility to study pentaquark states $P_c(4312), P_c(4440)$ and $P_c(4457)$ in $\gamma p \to J/\psi p$ reaction” arXiv:1904.11706 [hep-ph].

K. Jenkins et al., “A Search for the Reaction $\pi^+ p \to J/\psi n$ Near Threshold,” Phys. Rev. D 17, 52 (1978).

I. H. Chiang et al., “Search For Exclusive $J/\psi$ Production,” Phys. Rev. D 34, 1619 (1986).

A. Auspurgesil [GlueX Collaboration], “Light-Meson Spectroscopy at GlueX,” Int. J. Mod. Phys. Conf. Ser. 46, 1860029 (2018).

S. Kumano, “Spin Physics at J-PARC,” Int. J. Mod. Phys. Conf. Ser. 40, 1660009 (2016).

F. Nerling [COMPASS Collaboration], “Hadron Spectroscopy with COMPASS: Newest Results,” EPJ Web Conf. 37 (2012) 01016.

S. H. Kim, S. i. Nam, Y. Oh and H. C. Kim, “Contribution of higher nucleon resonances to $K^A$ photoproduction,” Phys. Rev. D 84, 114023 (2011).

Y. Oh, C. M. Ko and K. Nakayama, “Nucleon and Delta resonances in $K\Sigma(1385)$ photoproduction from nucleons,” Phys. Rev. C 77, 045204 (2008).

B. S. Zou and F. Hussain, “Covariant L-S scheme for the effective N*N couplings,” Phys. Rev. C 67, 034022 (2003).

Z. W. Lin, C. M. Ko and B. Zhang, “Hadronic scattering of charm mesons,” Phys. Rev. C 61, 024904 (2000).

V. Baru, C. Hanhart, M. Hofrichter, B. Kubis, A. Nogga and D. R. Phillips, “Precision calculation of threshold $\pi^+d$ scattering, $pN$ scattering lengths, and the GMO sum rule,” Nucl. Phys. A 872, 69 (2011).

J. J. Wu and T.-S. H. Lee, “Production of $J/\psi$ on the nucleon and on deuteron targets,” Phys. Rev. C 88, 015205 (2013).

X. Y. Wang and J. He, “Investigation of pion-induced $f_1(1285)$ production off a nucleon target within an interpolating Reggeized approach,” Phys. Rev. D 96, 034017 (2017).

X. H. Liu, Q. Zhao and F. E. Close, “Search for tetraquark candidate $Z(4430)$ in meson photoproduction,” Phys. Rev. D 77, 094005 (2008).

X. Y. Wang and J. He, “$K^0\Lambda$ photoproduction off a neutron,” Phys. Rev. C 93, 035202 (2016).

X. Y. Wang, J. He and H. Haberzettl, “Analysis of recent CLAS data on $\Sigma(1385)$ photoproduction off a neutron target,” Phys. Rev. C 93, 035204 (2016).

X. Y. Wang and J. He, “Analysis of recent CLAS data on $f_1(1285)$ photoproduction,” Phys. Rev. D 95, 094005 (2017).

X. Y. Wang, J. He, Q. Wang and H. Xu, “Productions of $f_1(1420)$ in pion and kaon induced reactions,” Phys. Rev. D 99, 014020 (2019).

H. Haberzettl, X. Y. Wang and J. He, “Preserving Local Gauge Invariance with t-Channel Regge Exchange,” Phys. Rev. C 92, 055503 (2015).

S. Ozaki, H. Nagahiro and A. Hosaka, “Charged K* Photoproduction in a Regge model,” Phys. Rev. C 81, 035206 (2010).