

Neutral hidden charm pentaquark states $P_c^0(4380)$ and $P_c^0(4450)$ in the $\pi^- p \rightarrow J/\psi n$ reaction

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We investigate the neutral hidden charm pentaquark states $P_c^0(4380)$ and $P_c^0(4450)$ in the $\pi^- p \rightarrow J/\psi n$ reaction within an effective Lagrangian approach. The background contributions for the process mainly come from t -channel π and ρ meson exchanges. The contributions of the $P_c^0(4380)$ and $P_c^0(4450)$ states give clear peak structures in the magnitude of $1 \mu\text{b}$ at center-of-mass energies 4.38 GeV and 4.45 GeV in the total cross sections. Hence, this reaction may provide a new platform to search for neutral P_c states. It is expected that our estimated total cross sections, together with the angular distributions, can be tested by future experiments at J-PARC.

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I. INTRODUCTION

Recently, the LHCb Collaboration observed two exotic structures in the $J/\psi p$ invariant mass spectrum in the $\Lambda_b^0 \rightarrow J/\psi K^- p$ process [1]. The lower state $P_c^+(4380)$ has a mass of $4380 \pm 8 \pm 29 \text{ MeV}$ and a width of $205 \pm 18 \pm 86 \text{ MeV}$, while the mass and width of the higher state $P_c^+(4450)$ are $4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$ and $39 \pm 5 \pm 19 \text{ MeV}$, respectively. Three pairs of possible spin-parity values are favored for $P_c^+(4380)$ and $P_c^+(4450)$, which are $(3/2^-, 5/2^+)$, $(3/2^+, 5/2^-)$, and $(5/2^+, 3/2^-)$.

Very recently, the LHCb Collaboration reported the branching fraction of the decay $\Lambda_b^0 \rightarrow J/\psi K^- p$ [2]. Together with the fractions of $P_c^+(4380)$ and $P_c^+(4450)$ in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decay measured previously, the branching ratios $\mathcal{B}(\Lambda_b^0 \rightarrow P_c^+ K^-) \mathcal{B}(P_c^+ \rightarrow J/\psi p)$ are determined as

$$\begin{aligned} & \mathcal{B}(\Lambda_b^0 \rightarrow P_c^+(4380) K^-) \mathcal{B}(P_c^+(4380) \rightarrow J/\psi p) \\ &= 2.56 \pm 0.22 \pm 1.28_{-0.36}^{+0.46} \times 10^{-5}, \end{aligned} \quad (1)$$

$$\begin{aligned} & \mathcal{B}(\Lambda_b^0 \rightarrow P_c^+(4450) K^-) \mathcal{B}(P_c^+(4450) \rightarrow J/\psi p) \\ &= 1.25 \pm 0.15 \pm 0.33_{-0.18}^{+0.22} \times 10^{-5}. \end{aligned} \quad (2)$$

The observations immediately create interest in theoretical works on these two states. Various interpretations, such

as loosely bound molecular states [3–8], compact pentaquark states [9–15], and anomalous triangle singularity effects [16–18], are respectively proposed. Those calculations mainly focus on the masses of P_c states, and a comprehensive discussion of various interpretations can be found in Ref. [19]. It should be noted that the hidden charm states with meson-baryon and meson-meson interactions have already been investigated by many works in the literature, in which the masses and decay widths are calculated [20–28]. These states are probably the partners of the observed P_c states.

Besides the static properties, the production mechanism of P_c states is also an important topic. There have been some studies on the production of hidden charm states before the observations of P_c states, in which only lower spin states are considered [29–34]. In the $\Lambda_b^0 \rightarrow J/\psi K^- p$ decay process, only charged P_c states can be observed. The $\gamma p \rightarrow J/\psi p$ reaction with charged P_c production was proposed by some theoretical works and is expected to be tested by the JLab experiment in the near future [35–37]. However, there are few works on the production of its neutral partners in the literature. In Refs. [14,38], the authors suggested that the neutral P_c states can be produced via the $\Lambda_b \rightarrow J/\psi \bar{K}^0 n$ decay process. This situation is different from the studies of Z_c , where both the charged and neutral $Z_c(3900)$, $Z_c(4020)$, $Z_c(4200)$, and $Z_c(4430)$, etc., have been discussed and analyzed in detail both experimentally and theoretically [39–46]. It is of great interest to search for the neutral P_c states in addition to the charged ones. We expect that the analyses of the $\pi^- p \rightarrow J/\psi n$ reaction at J-PARC could give information about the

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neutral ones and, therefore, provide a unique perspective on the nature of hidden charm P_c states.

In the present work, we study the production of neutral P_c states in the pion induced reaction with an effective Lagrangian approach. There have been several papers related to the exotic resonances at J-PARC [32–34,47]. In the pion beam experiments at J-PARC, the expected pion energy can reach up to 20 GeV in the laboratory frame [48] with high luminosity, which is enough to produce the P_c states via $\pi^- p$ collision, and therefore, the measurement at J-PARC can test our calculations particularly for the neutral P_c states.

This paper is organized as follows. In Sec. II, the formalisms and ingredients for our calculations are listed. The results of total and differential cross sections and discussions are presented in Sec. III. Finally, a short summary is given in the last section.

II. FORMALISMS AND INGREDIENTS

Here, we study the $\pi^- p \rightarrow J/\psi n$ reaction within an effective Lagrangian approach, which has been widely employed to investigate the pion induced reactions [32,47–54]. The relevant Feynman diagrams are depicted in Fig. 1. The s -channel P_c states with different spin-parity assumptions are involved in our analyses. The u -channel contributions are expected to be negligible due to the highly off-shell intermediate P_c states. The background contributions from the t channel via π and ρ meson exchanges are taken into account, while other meson exchanges in the t channel, such as $Z_c(3900)$, are simply ignored due to their unclear structures.

The effective Lagrangians for $P_c N J/\psi$ couplings can be written as [55]

$$\begin{aligned} \mathcal{L}_{P_c N J/\psi}^{3/2^\pm} = & -\frac{ig_1}{2M_N} \bar{N} \Gamma_\nu^{(\pm)} \psi^{\mu\nu} P_{c\mu} \\ & -\frac{g_2}{(2M_N)^2} \partial_\nu \bar{N} \Gamma^{(\pm)} \psi^{\mu\nu} P_{c\mu} \\ & +\frac{g_3}{(2M_N)^2} \bar{N} \Gamma^{(\pm)} \partial_\nu \psi^{\mu\nu} P_{c\mu} + \text{H.c.}, \end{aligned} \quad (3)$$

$$\begin{aligned} \mathcal{L}_{P_c N J/\psi}^{5/2^\pm} = & \frac{g_1}{(2M_N)^2} \bar{N} \Gamma_\nu^{(\mp)} \partial^\alpha \psi^{\mu\nu} P_{c\mu\alpha} \\ & -\frac{ig_2}{(2M_N)^3} \partial_\nu \bar{N} \Gamma^{(\mp)} \partial^\alpha \psi^{\mu\nu} P_{c\mu\alpha} \\ & +\frac{ig_3}{(2M_N)^3} \bar{N} \Gamma^{(\mp)} \partial^\alpha \partial_\nu \psi^{\mu\nu} P_{c\mu\alpha} + \text{H.c.}, \end{aligned} \quad (4)$$

where the vertex Γ matrix is defined as

$$\Gamma_\mu^{(\pm)} \equiv \begin{pmatrix} \gamma_\mu \gamma_5 \\ \gamma_\mu \end{pmatrix}, \quad (5)$$

$$\Gamma^{(\pm)} \equiv \begin{pmatrix} \gamma_5 \\ 1 \end{pmatrix}, \quad (6)$$

for positive and negative parities.

In our calculation, the higher partial wave terms in Eqs. (3) and (4) are neglected due to the small momentum of the final $J/\psi N$ state compared with nucleon mass and due to the lack of experimental data [35]. Therefore, we have only one unknown coupling g_1 . The effective Lagrangians for $P_c N \pi$ vertices are described in a Lorentz covariant orbital-spin scheme [56]:

$$\mathcal{L}_{P_c N \pi}^{3/2^+} = \frac{g_{P_c N \pi}}{m_\pi} \bar{N} \vec{\tau} \cdot \partial_\mu \vec{\pi} P_c^\mu + \text{H.c.}, \quad (7)$$

$$\mathcal{L}_{P_c N \pi}^{3/2^-} = \frac{g_{P_c N \pi}}{m_\pi^2} \bar{N} \gamma_5 \gamma_\mu \vec{\tau} \cdot \partial^\mu \partial_\nu \vec{\pi} P_c^\nu + \text{H.c.}, \quad (8)$$

$$\mathcal{L}_{P_c N \pi}^{5/2^+} = \frac{g_{P_c N \pi}}{m_\pi^3} \bar{N} \gamma_5 \gamma_\mu \vec{\tau} \cdot \partial^\mu \partial_\nu \partial_\lambda \vec{\pi} P_c^{\nu\lambda} + \text{H.c.}, \quad (9)$$

$$\mathcal{L}_{P_c N \pi}^{5/2^-} = \frac{g_{P_c N \pi}}{m_\pi^2} \bar{N} \vec{\tau} \cdot \partial_\mu \partial_\nu \vec{\pi} P_c^{\mu\nu} + \text{H.c.} \quad (10)$$

Furthermore, we adopt the commonly used Lagrangian densities for $J/\psi \pi \pi$, $J/\psi \pi \rho$, $\pi N N$, and $\rho N N$ vertices [49,57–60] in our t -channel calculation. They are

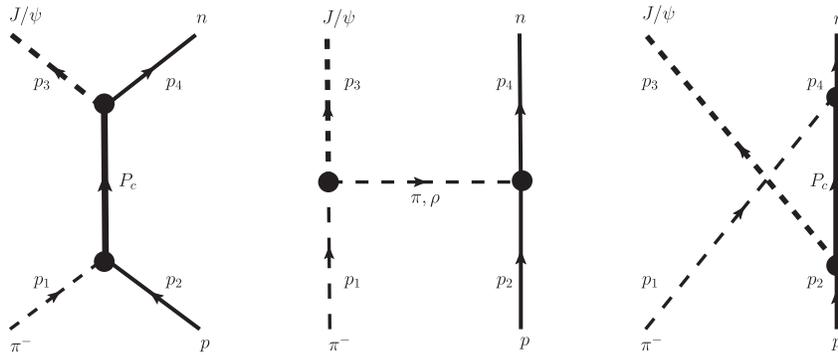


FIG. 1. Feynman diagrams for the $\pi^- p \rightarrow J/\psi n$ reaction.

$$\mathcal{L}_{J/\psi\pi\pi} = -ig_{J/\psi\pi\pi}(\partial^\mu\pi^-\pi^+ - \partial^\mu\pi^+\pi^-)\psi_\mu, \quad (11)$$

$$\mathcal{L}_{J/\psi\pi\rho} = -\frac{g_{J/\psi\pi\rho}}{m_{J/\psi}}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\rho_\nu\partial_\alpha\psi_\beta\pi, \quad (12)$$

$$\mathcal{L}_{\pi NN} = -\frac{g_{\pi NN}}{2M_N}\bar{N}\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi}N, \quad (13)$$

$$\mathcal{L}_{\rho NN} = -g_{\rho NN}\bar{N}\left(\gamma_\mu + \frac{\kappa}{2M_N}\sigma_{\mu\nu}\partial^\nu\right)\vec{\tau}\cdot\partial^\mu\vec{\rho}N. \quad (14)$$

In this work, the decay processes of $P_c \rightarrow NJ/\psi$ and $P_c \rightarrow N\pi$ are calculated and the relevant coupling constants g_1 ($\equiv g_{P_c NJ/\psi}$) and $g_{P_c N\pi}$ can be obtained from their partial decay widths with different J^P assignments of P_c . The obtained coupling constants are listed in Table I, by assuming that the branching ratios are 10% and 1% for the $P_c \rightarrow NJ/\psi$ and $P_c \rightarrow N\pi$, respectively. In the calculation, we employ the total widths of the two P_c states from experimental measurements with $\Gamma_{P_c(4380)} = 205$ MeV and $\Gamma_{P_c(4450)} = 39$ MeV.

The coupling constants of $J/\psi\pi\rho$, $J/\psi\pi\pi$, πNN , and ρNN are needed as well in our calculation, and we select $g_{J/\psi\pi\pi} = 8.20 \times 10^{-4}$, $g_{J/\psi\pi\rho} = 0.032$, $g_{\pi NN} = 13.45$, $g_{\rho NN}^2/(4\pi) = 0.9$ and $\kappa = 6.1$ according to Refs. [49,60].

The propagators for exchanged π and ρ mesons are

$$G_\pi(q) = \frac{i}{q^2 - m_\pi^2}, \quad (15)$$

$$G_\rho^{\mu\nu}(q) = i\frac{-g^{\mu\nu} + q^\mu q^\nu/m_\rho^2}{q^2 - m_\rho^2}. \quad (16)$$

For the propagator of spin-3/2 fermion, we use

$$G^{\beta\alpha}(q) = \frac{i(\not{q} + M)P^{\beta\alpha}(q)}{q^2 - M^2 + iM\Gamma}, \quad (17)$$

with

$$P^{\beta\alpha}(q) = -g^{\beta\alpha} + \frac{1}{3}\gamma^\beta\gamma^\alpha + \frac{1}{3M}(\gamma^\beta q^\alpha - \gamma^\alpha q^\beta) + \frac{2}{3M^2}q^\beta q^\alpha, \quad (18)$$

and for the propagator of the spin-5/2 fermion, it is

$$G^{\rho\sigma\alpha\beta}(q) = \frac{i(\not{q} + M)P^{\rho\sigma\alpha\beta}(q)}{q^2 - M^2 + iM\Gamma}, \quad (19)$$

with

$$P^{\rho\sigma\alpha\beta}(q) = \frac{1}{2}(\tilde{g}^{\rho\alpha}\tilde{g}^{\sigma\beta} + \tilde{g}^{\rho\beta}\tilde{g}^{\sigma\alpha}) - \frac{1}{5}\tilde{g}^{\rho\sigma}\tilde{g}^{\alpha\beta} - \frac{1}{10}(\tilde{\gamma}^\rho\tilde{\gamma}^\alpha\tilde{g}^{\sigma\beta} + \tilde{\gamma}^\rho\tilde{\gamma}^\beta\tilde{g}^{\sigma\alpha} + \tilde{\gamma}^\sigma\tilde{\gamma}^\alpha\tilde{g}^{\rho\beta} + \tilde{\gamma}^\sigma\tilde{\gamma}^\beta\tilde{g}^{\rho\alpha}), \quad (20)$$

where

$$\tilde{g}^{\alpha\beta} = g^{\alpha\beta} - \frac{P^\alpha P^\beta}{M^2} \quad (21)$$

and

$$\tilde{\gamma}^\alpha = \gamma^\alpha - \frac{P^\alpha}{M^2}\not{P}. \quad (22)$$

From the above Lagrangian densities, the s -channel amplitude for each J^P assignment of P_c states can be obtained,

$$\begin{aligned} \mathcal{M}^{3/2^+} &= \frac{ig_{P_c NJ/\psi}\sqrt{2}g_{P_c N\pi}}{2M_N m_\pi}F(q^2)\epsilon_\nu^*(p_3, s_3) \\ &\times \bar{u}(p_4, s_4)\gamma_\sigma\gamma_5(p_3^\beta g^{\mu\sigma} - p_3^\sigma g^{\beta\nu}) \\ &\times G_{\beta\alpha}(q)p_1^\alpha u(p_2, s_2), \end{aligned} \quad (23)$$

$$\begin{aligned} \mathcal{M}^{3/2^-} &= \frac{ig_{P_c NJ/\psi}-\sqrt{2}g_{P_c N\pi}}{2M_N m_\pi^2}F(q^2)\epsilon_\nu^*(p_3, s_3) \\ &\times \bar{u}(p_4, s_4)\gamma_\sigma(p_3^\beta g^{\mu\sigma} - p_3^\sigma g^{\beta\nu}) \\ &\times G_{\beta\alpha}(q)\gamma_5\not{p}_1 p_1^\alpha u(p_2, s_2), \end{aligned} \quad (24)$$

$$\begin{aligned} \mathcal{M}^{5/2^+} &= \frac{-ig_{P_c NJ/\psi}-\sqrt{2}g_{P_c N\pi}}{(2M_N)^2 m_\pi^3}F(q^2)\epsilon_\nu^*(p_3, s_3) \\ &\times \bar{u}(p_4, s_4)\gamma_\delta p_3^\sigma(p_3^\rho g^{\nu\delta} - p_3^\delta g^{\rho\nu}) \\ &\times G_{\rho\sigma\alpha\beta}(q)\gamma_5\not{p}_1 p_1^\alpha p_1^\beta u(p_2, s_2), \end{aligned} \quad (25)$$

$$\begin{aligned} \mathcal{M}^{5/2^-} &= \frac{-ig_{P_c NJ/\psi}-\sqrt{2}g_{P_c N\pi}}{(2M_N)^2 m_\pi^2}F(q^2)\epsilon_\nu^*(p_3, s_3) \\ &\times \bar{u}(p_4, s_4)\gamma_\delta\gamma_5 p_3^\sigma(p_3^\rho g^{\nu\delta} - p_3^\delta g^{\rho\nu}) \\ &\times G_{\rho\sigma\alpha\beta}(q)p_1^\alpha p_1^\beta u(p_2, s_2). \end{aligned} \quad (26)$$

TABLE I. Coupling constants of $P_c NJ/\psi$ and $P_c N\pi$ different J^P assignments by assuming the branching ratios are 10% and 1%, respectively.

State	Channel	3/2 ⁺	3/2 ⁻	5/2 ⁺	5/2 ⁻
$P_c(4380)$	$J/\psi N$	1.09	0.49	2.17	5.13
	πN	8.56×10^{-3}	3.43×10^{-4}	3.59×10^{-5}	8.95×10^{-4}
$P_c(4450)$	$J/\psi N$	0.41	0.20	0.80	1.75
	πN	3.65×10^{-3}	1.43×10^{-4}	1.47×10^{-5}	3.75×10^{-4}

Here, p_1, p_2, p_3 , and p_4 are the four momenta of the pion, proton, J/ψ , and neutron, respectively; s_2, s_3 , and s_4 are the spin projections of the proton, J/ψ , and neutron, respectively; $q = p_1 + p_2$ is the four momentum of the intermediate P_c states.

In addition, the background t -channel π and ρ meson exchange amplitudes are

$$\mathcal{M}_\pi = \frac{\sqrt{2}ig_{J/\psi\pi\pi}g_{\pi NN}}{M_N} F_\pi^{NN}(q_\pi^2)F_\pi^{J/\psi\pi}(q_\pi^2)\epsilon_\nu^*(p_3, s_3) \times p_1^\nu G_\pi(q)\bar{u}(p_4, s_4)\gamma_5\mathcal{Q}_\pi u(p_2, s_2), \quad (27)$$

$$\mathcal{M}_\rho = \frac{\sqrt{2}g_{J/\psi\rho\rho}g_{\rho NN}}{M_{J/\psi}} F_\rho^{NN}(q_\rho^2)F_\rho^{J/\psi\pi}(q_\rho^2)\epsilon_\nu^*(p_3, s_3) \times \epsilon^{\alpha\beta\mu\nu}q_{\rho\alpha}p_{3\mu}G_{\rho\beta\lambda}(q)\bar{u}(p_4, s_4) \times \left[\gamma^\lambda + \frac{\kappa}{4M_N}(\gamma^\lambda\mathcal{Q}_\rho - \mathcal{Q}_\rho\gamma^\lambda) \right] u(p_2, s_2), \quad (28)$$

where $q_\pi = p_1 - p_3$ and $q_\rho = p_1 - p_3$ are the four momentum of π and ρ mesons, respectively.

In our calculations, phenomenological form factors are needed since the hadrons are not pointlike particles. The form factors $F(q^2)$, $F_M^{NN}(q_M^2)$, and $F_M^{J/\psi\pi}(q_M^2)$ can be expressed as

$$F(q^2) = \frac{\Lambda_{P_c}^4}{\Lambda_{P_c}^4 + (q^2 - M_{P_c}^2)^2}, \quad (29)$$

$$F_M^{J/\psi\pi}(q_M^2) = \frac{\Lambda_M^{*2} - m_M^2}{\Lambda_M^{*2} - q_M^2}, \quad (30)$$

$$F_M^{NN}(q_M^2) = \left(\frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - q_M^2} \right)^n, \quad (31)$$

with $n = 1$ for the π meson and $n = 2$ for the ρ meson [49]. We use the cutoff parameters $\Lambda_{P_c} = 0.5$ GeV for P_c states [35,55], and $\Lambda_\pi^* = \Lambda_\pi^* = 1.3$ GeV, $\Lambda_\rho = 1.6$ GeV, and $\Lambda_\pi = 1.3$ GeV for mesons [49].

The unpolarized differential cross section in the c.m. frame for the $\pi^- p \rightarrow J/\psi n$ reaction is

$$\frac{d\sigma}{d\cos\theta} = \frac{M_N^2}{16\pi s} \frac{|\vec{p}_3^{\text{c.m.}}|}{|\vec{p}_1^{\text{c.m.}}|} |\mathcal{M}_{\pi^- p \rightarrow J/\psi n}|^2, \quad (32)$$

where θ is the scattering angle of outgoing J/ψ relative to the incoming pion beam, and $\vec{p}_1^{\text{c.m.}}$ and $\vec{p}_3^{\text{c.m.}}$ are the three momenta of π and J/ψ mesons in the c.m. frame. The relative phases between different amplitudes are unknown [61]. The interference terms with different choices of relative phases are calculated, and the theoretical uncertainties for the total cross sections are presented.

III. RESULTS AND DISCUSSIONS

Figure 2 gives the total cross sections for the $\pi^- p \rightarrow J/\psi n$ reaction with different J^P assignments from threshold up to 5 GeV of the c.m. energy. Besides the t -channel π and ρ meson exchanges, the s -channel $P_c^0(4380)$ and $P_c^0(4450)$ contributions are explicitly presented. In the figure, the green dashed, blue dot-dashed, and pink short dotted lines stand for $P_c^0(4380)$, $P_c^0(4450)$, and background contributions, respectively. The red solid bands stand for the total cross sections due to the unknown relative phases between different amplitudes. It should be noted that the $(5/2^-, 3/2^+)$ assumption for $[P_c(4380), P_c(4450)]$ shown in Fig. 2(d) is not favored by experiments [1]. The P_c states are first observed in the $J/\psi p$ invariant mass, and the $P_c \rightarrow J/\psi N$ decay processes can occur via the falling apart mechanism. For the πN decay channel, these processes are OZI-allowed and two-body strong decays with large phase spaces. Large decay branching ratios are expected if no $c\bar{c}$ pair annihilation is considered. The suppression due to the $c\bar{c}$ pair annihilation can be estimated by a factor of $(m_u/m_c)^2$, where m_u and m_c are the constituent quark masses of the light quark and charm quark, respectively. This assumption has been widely used in the quark pair creation model [62–64]. The value of $(m_u/m_c)^2$ is about 1/20 in the traditional quark model [63,64]. Hence, our assumptions of $\mathcal{B}(P_c \rightarrow J/\psi N) = 10\%$ and $\mathcal{B}(P_c \rightarrow \pi N) = 1\%$ are reasonable.

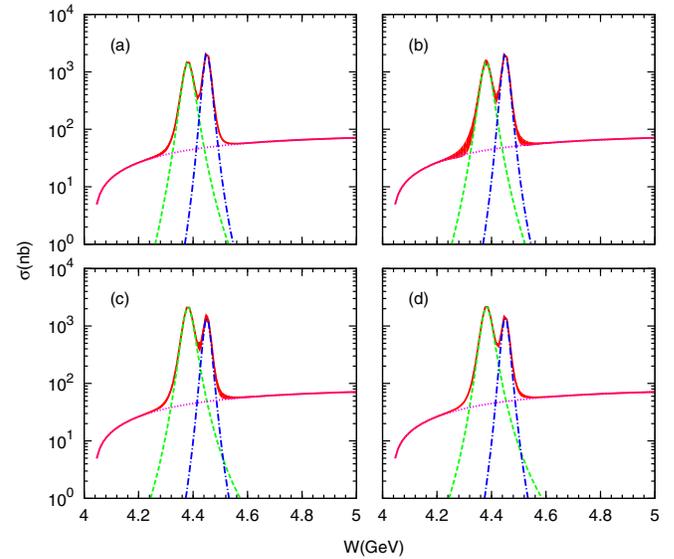


FIG. 2. The total cross sections for the $\pi^- p \rightarrow J/\psi n$ reaction with different J^P assumptions versus c.m. energy. The green dashed, blue dot-dashed, and pink short dotted lines stand for $P_c^0(4380)$, $P_c^0(4450)$, and background contributions, respectively. The thin red solid bands are total cross sections with the consideration of the interferences. Panels (a–d) correspond to $(3/2^+, 5/2^-)$, $(3/2^-, 5/2^+)$, $(5/2^+, 3/2^-)$, $(5/2^-, 3/2^+)$ assumptions for $[P_c^0(4380), P_c^0(4450)]$, respectively.

From Fig. 2, it can be seen that the π and ρ meson exchanges provide a significant background contribution, while the two narrow bump structures come from $P_c^0(4380)$ and $P_c^0(4450)$ contributions. The thin bands for total cross sections indicate that the interference effects among the different contributions are extremely small. At c.m. energies of $W = 4.38$ GeV and 4.45 GeV, which are the regions with which we are mainly concerned, these effects are invisible and can be ignored. Hence, we only present the direct summations of each contribution in the following differential cross sections. With different J^P assignments, the divergences among these total cross sections are small and can hardly be used to identify the spin parities of the two P_c states. The peaks, in the figure, are of the magnitude $1 \mu\text{b}$ at the c.m. energies $W = 4.38$ GeV and 4.45 GeV, which can be measured in future high luminosity J-PARC experiments.

It is worth mentioning that the contributions from neutral P_c resonances are proportional to the branching ratios of $J/\psi N$ and πN decay modes. In Ref. [35], the low limit of the $P_c \rightarrow J/\psi N$ ratio is assumed to be 5%. If the same low limit is employed, the present calculated total cross sections will be reduced by a factor of 2; however, the clear bump structures remain. For the cutoff parameter of P_c states, a relatively small value is employed, which is more suitable for heavy meson production [35,55]. If this value increases, the contributions of two P_c states will become larger. Actually, the form factor is approximate equal to 1 at resonance energy regions despite the cutoff value, since $q^2 - M_{P_c}^2 \sim 0$. Our conclusions of the total and following

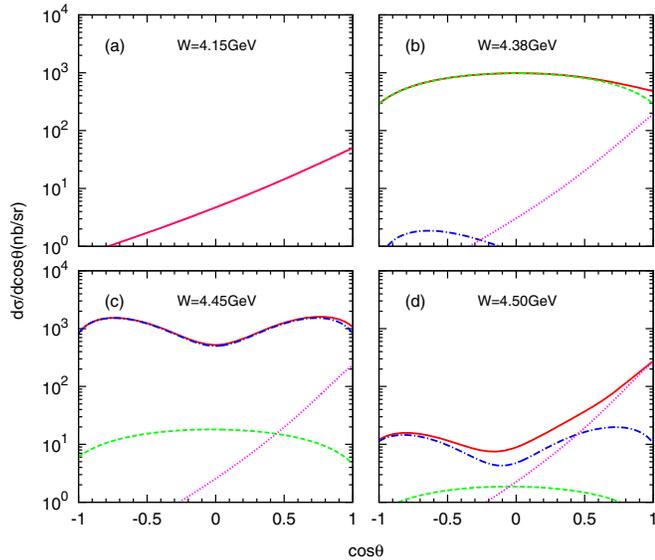


FIG. 3. The differential cross sections for the $\pi^- p \rightarrow J/\psi n$ reaction at the c.m. energies $W = 4.15$ GeV, 4.38 GeV, 4.45 GeV, and 4.45 GeV. The $[P_c^0(4380), P_c^0(4450)]$ corresponds to the $(3/2^+, 5/2^-)$ assumption. The red solid, green dashed, blue dot-dashed, and pink short dotted lines stand for total, $P_c^0(4380)$, $P_c^0(4450)$, and background contributions, respectively.

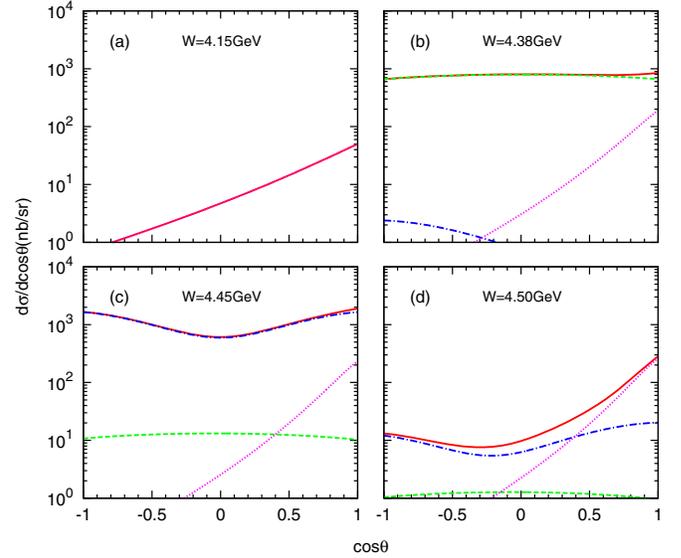


FIG. 4. The caption is the same as that of Fig. 3, but the $[P_c^0(4380), P_c^0(4450)]$ corresponds to the $(3/2^-, 5/2^+)$ assumption.

differential cross sections remain while this cutoff parameter changes.

The differential cross sections at the c.m. energies $W = 4.15$ GeV, 4.38 GeV, 4.45 GeV, and 4.45 GeV are also presented in Figs. 3–6. It is shown that the t -channel meson exchanges provide forward contribution in the whole energy region and play a predominant role near the threshold. The differential cross sections at 4.38 GeV and 4.45 GeV are mainly from $P_c^0(4380)$ and $P_c^0(4450)$ contributions, respectively, which are also revealed by the

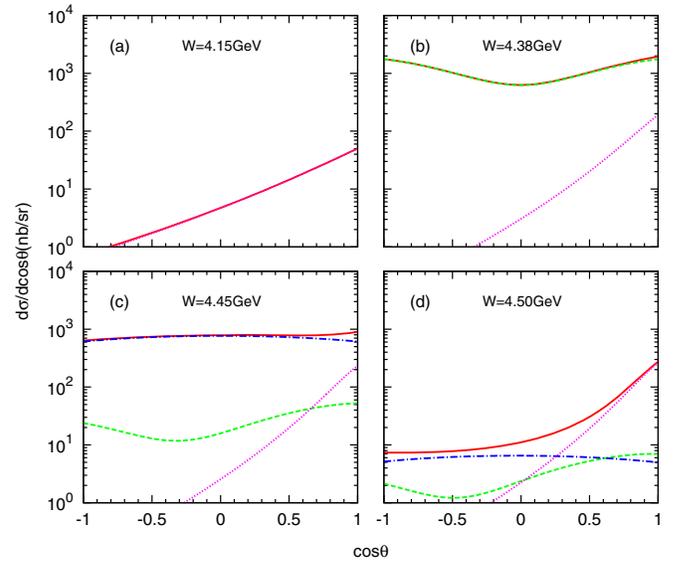


FIG. 5. The caption is the same as that of Fig. 3, but the $[P_c^0(4380), P_c^0(4450)]$ corresponds to the $(5/2^+, 3/2^-)$ assumption.

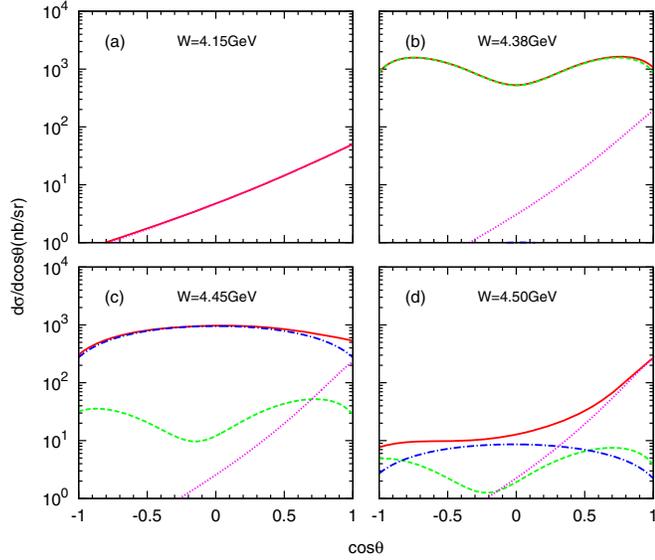


FIG. 6. The caption is the same as that of Fig. 3, but the $[P_c^0(4380), P_c^0(4450)]$ corresponds to the $(5/2^-, 3/2^+)$ assumption.

total cross sections. The angular distributions of the two P_c resonances are obviously different than the forward background contribution and display significantly different behaviors with different J^P assignments. It is expected that those specific features can be observed by future J-PARC experiments with high luminosity, and can help us to distinguish different spin-parity assignments.

IV. SUMMARY

In this paper, the $\pi^- p \rightarrow J/\psi n$ reaction is studied, within an effective Lagrangian approach, in order to search for the neutral hidden charm pentaquark P_c states. The background contribution mainly comes from t -channel π and ρ meson exchanges. For the s -channel diagram, the P_c states with different spin-parity assignments are calculated and analyzed. We find that the two states contribute clear bump structures in the total cross sections. Moreover, we also find that the differential cross sections of the P_c states have significant divergences from the background contribution, and we explicitly show the different behaviors among the four spin-parity assumptions. Those specific features of the angular distributions, together with the total cross sections with clear peak structures of the magnitude $1 \mu\text{b}$ at c.m. energies 4.38 GeV and 4.45 GeV, can be tested by future experiments at J-PARC.

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