Looking for the hidden-charm pentaquark resonances in $J/\psi p$ scattering

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In the framework of quark delocalization color screening model, the three new reported pentaquarks $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ can be identified as the hidden-charm molecular states with $J^P = \frac{3}{2}^-$, $\Sigma_c D$ with $J^P = \frac{1}{2}^+$, and $\Sigma_c D^*$ with $J^P = \frac{1}{2}^-$, in the baryon-meson scattering process, respectively. Besides, the $\Sigma_c D^*$ of both $J^P = \frac{1}{2}^-$ and $J^P = \frac{1}{2}^-$ are also possible molecular pentaquarks. Moreover, the calculation is extended to the $P_c$-like molecular pentaquarks $P_c$. Several states with masses above 11 GeV and narrow width are obtained. All these heavy pentaquarks are worth searching in the future experiments.

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I. INTRODUCTION

In 2015, the claim of two hidden-charm pentaquark states $P_c(4380)$ and $P_c(4450)$ by the LHCb Collaboration attracted people’s interest in the pentaquarks with heavy quarks and inspired a lot of theoretical work on these two states, such as the baryon-meson molecules, the diquark-triquark pentaquarks, the diquark-diquark-antiquark pentaquarks, the genuine multiquark states, the topological soliton, and the kinematical threshold effects in the triangle singularity mechanism, and so on. The lattice QCD simulation of $NJ/\psi$ and $N_{bc}$ scattering is also performed to find these $P_c$ states.

Four years later, at the Rencontres de Moriond QCD Conference, the LHCb Collaboration reported the observation of three new pentaquarks, named as $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$. The $P_c(4312)$ was discovered with 7.3σ significance by analyzing the $J/\psi p$ invariant mass spectrum. The previously reported $P_c(4440)$ structure was resolved at 5.4σ significance into two narrow states; the $P_c(4440)$ and $P_c(4457)$. The masses and widths of these states are:

$P_c(4312) : M = 4311.9 \pm 0.7 ^{+6.8}_{-5.0} \text{ MeV},$
$\Gamma = 9.8 \pm 2.7 ^{+3.7}_{-4.5} \text{ MeV},$

$P_c(4440) : M = 4440.3 \pm 1.3 ^{+1.1}_{-1.2} \text{ MeV},$
$\Gamma = 20.6 \pm 4.9 ^{+8.7}_{-10.1} \text{ MeV},$

$P_c(4457) : M = 4457.3 \pm 0.6 ^{+1.3}_{-1.2} \text{ MeV},$
$\Gamma = 6.4 \pm 2.0 ^{+5.7}_{-1.9} \text{ MeV}. \quad (1)$

As mentioned in Ref. [37], since all three states are narrow and below the $\Sigma_c^+ D^0$ and $\Sigma_c^+ D^{*0}$ thresholds within plausible hadron-hadron binding energies, they provide the strongest experimental evidence to date for the existence of molecular states composed of a charmed baryon and an anticharmed meson. Immediately after the report of the LHCb Collaboration, several theoretical work have been done to study the mass spectrum of these states [38–40]. Ref. [41] studied the isospin breaking decays of the molecular structure of the $P_c(4457)$.

Searching for the existence of multiquark states is an important issue of the hadron physics. To provide the necessary information for experiments, mass spectrum calculation alone is not enough. The study of hadron-hadron scattering, as well as the main production process of multiquark states, is indispensable. In the framework of the quark delocalization color screening model (ODCSM), the detail of which can be found in Refs. [42,43], we apply the well developed resonating group method (RGM) [44] to calculate the baryon-meson scattering phase shifts and to find the hidden-charm and hidden-bottom pentaquark resonances. The wave function of the baryon-meson system is of the form

$$\Psi = A \left[ \phi_A(\xi_1, \xi_2) \phi_B(\xi_3) \chi_L(R_{AB}) \right]. \quad (2)$$

where $\xi_1$ and $\xi_2$ are the internal coordinates for the baryon cluster $A$, and $\xi_3$ is the internal coordinate for the meson cluster $B$. $R_{AB} = R_A - R_B$ is the relative coordinate between the two clusters. The $\phi_A$ and $\phi_B$ are the internal cluster wave functions of the baryon $A$ (antisymmetrized) and meson $B$, and $\chi_L(R_{AB})$ is the relative motion wave function between two clusters. The symbol $A$ is the anti-symmetrization operator defined as

$$A = 1 - P_{14} - P_{24} - P_{34}, \quad (3)$$

where 1, 2, and 3 stand for the quarks in the baryon cluster and 4 stands for the quark in the meson cluster. For a bound-state problem, $\chi_L(R_{AB})$ is expanded by gaussian bases

$$\chi_L(R_{AB}) = \frac{1}{\sqrt{4\pi}} \left( \frac{6}{5\pi b^2} \right)^{3/4} \sum_{i=1}^{n} C_i \times \int \exp \left[ -3 \left( \frac{R_{AB} - S_i}{b} \right)^2 \right] Y_{LM}(\hat{S}_i) d\hat{S}_i$$

$$= \sum_{i=1}^{n} C_i \frac{y_{LM}(R_{AB}, S_i)}{R_{AB}} Y_{LM}(\hat{R}_{AB}). \quad (4)$$
By solving Eq. (8), we can obtain the expansion coefficients which are determined by the smoothness of the results, and $j_L$ is the $L$-th spherical Bessel function.

For a scattering problem, the relative wave function is expanded as

$$\chi_L(R_{AB}) = \sum_{i=1}^{n} C_i \frac{\tilde{u}_L(R_{AB}, S_i)}{R_{AB}} Y_{LM}(\hat{R}_{AB}).$$

where $h_L^\pm$ is the $L$-th spherical Hankel functions, $k_{AB}$ is the momentum of relative motion with $k_{AB} = \sqrt{2 \mu_{AB} E_{cm}}$, $\mu_{AB}$ is the reduced mass of two hadrons (A and B) of the open channel; $E_{cm}$ is the incident energy, and $R_C$ is a cutoff radius beyond which all the strong interaction can be disregarded. Besides, $\alpha_i$ and $s_i$ are complex parameters which are determined by the smoothness condition at $R_{AB} = R_C$ and $C_i$ satisfy $\sum_{i=1}^{n} C_i = 1$. After performing variational procedure, a $L$-th partial-wave equation for the scattering problem can be deduced as

$$\sum_{j=1}^{n} \mathcal{L}_{ij} C_j = \mathcal{M}_i^L \quad (i = 0, 1, \cdots, n - 1),$$

with

$$\mathcal{L}_{ij} = \mathcal{K}_{ij}^L - \mathcal{K}_{i0}^L - \mathcal{K}_{ij}^{L*} + \mathcal{K}_{i0}^{L*},$$

$$\mathcal{M}_i^L = \mathcal{K}_{i0}^L - \mathcal{K}_{i0}^{L*}.$$  

and

$$\mathcal{K}_{ij}^L = \left\langle \phi_A(\xi_1, \xi_2) \phi_B(\xi_3) \frac{\tilde{u}_L(R_{AB}, S_i)}{R_{AB}} Y_{LM}(\hat{R}_{AB}) \right\rangle_{|H - E|}$$

$$\times \left\langle \phi_A(\xi_1, \xi_2) \phi_B(\xi_3) \frac{\tilde{u}_L(R_{AB}, S_i)}{R_{AB}} Y_{LM}(\hat{R}_{AB}) \right\rangle.$$  

By solving Eq. (8), we can obtain the expansion coefficients $C_i$. Then the $S$ matrix element $S_L$ and the phase shifts $\delta_L$ are given by

$$S_L \equiv e^{2i\delta_L} = \sum_{i=1}^{n} C_i s_i,$$

Resonances are unstable particles usually observed as bell-shaped structures in scattering cross sections of their corresponding open channels. For a simple narrow resonance, the peak position and the of the half-width of the bell shape are the mass $M$ and the decay width $\Gamma$ of the resonance. The cross-section $\sigma_L$ and the scattering phase shifts $\delta_L$ have relations:

$$\sigma_L = \frac{4\pi}{k^2} (2L + 1) \sin^2 \delta_L,$$

where $k = \sqrt{2 \mu E_{cm}/\hbar}$; $\mu$ is the reduced mass of two hadrons of the open channel; $E_{cm}$ is the incident energy. Therefore, by using the scattering phase shifts, the cross sections can be easily obtained. The scattering phase shifts are shown in our previous work [43]. Here, to compare with the experimental data, we calculate the cross sections of the $J/\psi p$ scattering, which are shown in Fig. 1. Based on our previous theoretical work, the new experimental information and the calculated cross sections, we discuss possible explanations of the three new pentaquarks: $P_1(4312), P_2(4440)$, and $P_3(4457)$.

For $P_1(4312)$, our previous study showed that there was a narrow resonance state $\Sigma_c^0 D$ with $J^P = \frac{1}{2}^-$ in the scattering channels of $\eta p$, $J/\psi p$, $\Lambda_c D$ and $\Lambda_c D^*$. The calculated mass of this resonance state is $4306.7 \pm 3$ MeV, and the decay width is $7.1$ MeV. From the Fig. 1(a), we also see a sharp peak appearing at the mass of $4307.9$ MeV with a very narrow partial width of about $1.2$ MeV. It is obvious that both the mass and decay widths are close to the experimental value of the $P_1(4312)$, which indicates that the newly reported $P_1(4312)$ state can be identified as the $\Sigma_c^0 D$ molecular pentaquark with $J^P = \frac{1}{2}^-$ in our model calculation.

For $P_2(4440)$ and $P_3(4457)$, we assigned them as the resonances $\Sigma_c^* D^*$ with $J^P = \frac{1}{2}^-$ and $\Sigma_c^* D^*$ with $J^P = \frac{3}{2}^-$ according to our calculation [43]. These two resonances also appear as two sharp peaks in the cross section of the $J/\psi p$ channel (see Fig. 1 (a) and (b)). The masses and the partial decay widths can be read from Fig. 1, they are: $\Sigma_c^* D^*$ of $J^P = \frac{1}{2}^-$, $4459.7$ MeV and $3.9$ MeV; $\Sigma_c^* D^*$ of $J^P = \frac{3}{2}^-$, $4445.7$ MeV and $1.5$ MeV. Compared with experimental data, the $P_2(4440)$ is more possible to be the molecular pentaquark $\Sigma_c^* D^*$ of $J^P = \frac{1}{2}^-$, and the $P_3(4457)$ can be explained as the molecular pentaquark $\Sigma_c^* D^*$ of $J^P = \frac{3}{2}^-$. Besides the three resonances discussed above, one may see the fourth peak showed in Fig. 1 (b). It is the molecular pentaquark $\Sigma_c^* D$ with $J^P = \frac{1}{2}^-$. The mass of this resonance is $4376.4$ MeV, which is very close to the reported $P_4(4380)$. However, the decay width is only $1.5$ MeV, much smaller than the experimental value. We propose the experiment to find whether there is any narrow resonance near the $P_4(4380)$.

In addition, in Fig. 1(a), we also find there is a cusp near the mass of $4527$ MeV, which is the threshold of the $\Sigma_c^* D^*$. Our previous calculation showed that the single
The three new narrow pentaquarks have the similar properties with the hidden-charm pentaquarks, so we can call them molecular pentaquarks Σ∗. This is consistent with the experimental result, there is no any distinct signal near the threshold of the Σ∗. Moreover, the Σ∗ has the mass of 11125 MeV and a width of 4.0 MeV, respectively. Besides, the Σ∗ has has the similar situation. It appears as a cusp in the cross section of the J/ψ scattering process. For the hidden-bottom pentaquarks with charm quarks can also be observed by the PANDA/FAIR [47]. For the pentaquarks with charm quarks, which are also worth searching for by experiments.

To summarize, in the framework of QDCSM, we look for the hidden-charm and hidden-bottom pentaquark resonances by studying J/ψp and Υp scattering process. The three new narrow pentaquarks Pc(4312), Pc(4440), and Pc(4457) observed in the process of Λb → J/ψpK reported by LHCb can be interpreted as the hidden-charm molecular pentaquarks Σ∗D with JP = 1−, ΣcD∗ with JP = 3−, and ΣcD∗ with JP = 1−, respectively. Another molecular pentaquark Σ∗D with JP = 3− is also existed in our calculation, the mass of which is close to the Pc(4380), but the width is much smaller than it. Besides, the Σ∗D of both JP = 1− and JP = 3− are possible molecular pentaquarks. All these narrow pentaquarks are worth searching for or being confirmed in future experiments. The Jefferson Lab has proposed to look for the hidden-charm pentaquarks by using photo-production of J/ψ at threshold in Hall C [46]. Moreover, the pentaquarks with charm quarks can also be observed by the PANDA/FAIR [47]. For the pentaquarks with charm quarks.
the hidden-bottom, we predict several $P_c$–like molecular pentaquarks $P_c$ above 11 GeV with narrow width. We hope the proposed electron-ion collider (EIC) [48] and the upgraded facilities at Jefferson Lab [49] can play important role in discovering these interesting super-heavy pentaquarks.

Searching for multiquark states is an important topic in hadron physics. To provide more information for experiments, the baryon-meson scattering process calculation is expected. Doing baryon-meson scattering is also a challenge for quark model. The model is needed to describe the baryon and meson spectra at the same time. With the accumulation of more experimental data on baryon-meson scattering and the pentaquark, the quark model will be further updated. To use the simple picture to describe the natural phenomena is one of the goal of physics.

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