P_c pentaquarks in a hybrid model of chiral and quark dynamics

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In this article we report our recent achievement in the collaboration for the pentaquark P_c's. A unique feature of our study is a hybrid picture where the long distance structure of hadronic molecule driven by the one pion exchange potential (OPEP) and the short range structure of five quarks dominated by the color force mediated by the gluons. The dynamics due to the pion is the necessity of the spontaneous symmetry breaking (SSB) of chiral symmetry. We emphasize the role of the tensor component of the OPEP both in their mass ordering and decay widths. The former is crucial for the determination of spin and parity of the observed P_c.

INTRODUCTION

In the past decades the Large Hadron Collider (LHC) has been producing a large amount of new hadron data indicating the existence of hadrons that have the structure beyond the minimal contents of the standard quark model: $\bar{q}q$ for mesons and qqq for baryons, where q denotes one of any kinds of quarks. The colliding energy of order 10 TeV enables to produce many bottom quarks which subsequently decay weakly into charm quarks. Among many of them, in this report we discuss the candidate of the hidden charm pentaquarks P_c whose minimal content is considered to be $\bar{c}cqqq$, where c is the charm quark and q is one of u, d quarks. This report is based on our collaboration that has been supported in part by the RCNP COREnet project.

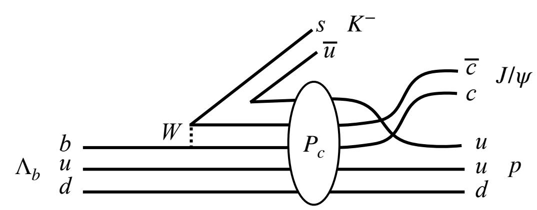

FIG. 1. A postulated quark diagram of the weak decay $\Lambda_b^0 \to J/\psi K^- p$.

The first report from LHCb group came in 2015 [1] with evidence of two P_c's. They studied the three-body decay

$$\Lambda_b^0 \to J/\psi K^- p \tag{1}$$

and performed the invariant mass analysis for $J/\psi p$. A postulated quark diagram is shown in Fig. 1. There, they observed nontrivial structures at masses around 4380 MeV and 4450 MeV. The data is shown in the upper panel of Fig. 2, where the higher peak at around 4450 MeV is evident, while the lower one at around 4380 MeV came from their detailed amplitude analysis. Being observed in $J/\psi p$ events, the structure is naturally associated to resonances containing five quarks of $c\bar{c}uud$, thus named P_c.

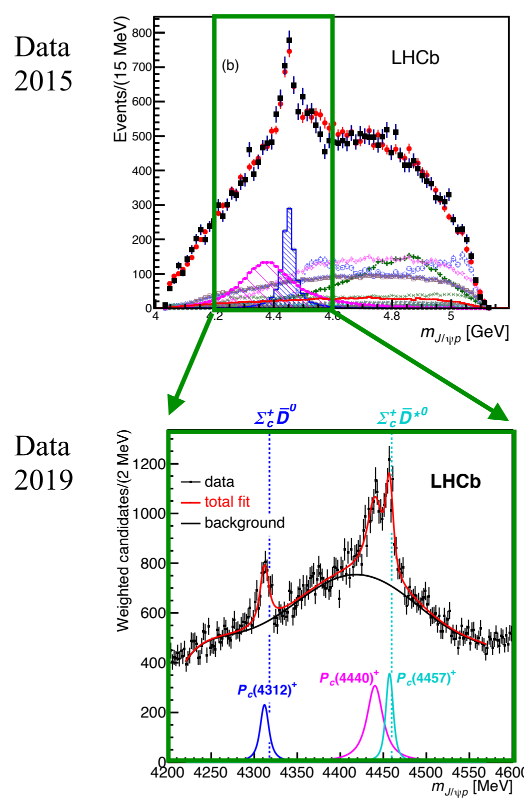

FIG. 2. Invariant mass spectrum of $J\psi p$ in the weak decay of $\Lambda_b^0 \to J/\psi K^- p$. Data are taken from Refs. [1, 2]

In 2019, they have reported higher statistics data refining their analysis with three narrow peaks as shown in the lower panel of Fig. 2 [2]. Their locations and widths are

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

The previous higher peak at 4450 MeV splits into two peaks at 4440 MeV and 4457 MeV. The previous lower signal at 4380 MeV is still kept, but now a new single peak at 4312 MeV has been unveiled.

These results are very suggestive as they are all located very close to two-hadron thresholds,

$$\begin{aligned}
\Sigma_c \bar{D} &\sim 4320 \quad \text{MeV} \\
\Sigma_c \bar{D}^* &\sim 4463 \quad \text{MeV}
\end{aligned} \tag{2}$$

having lead to the idea that these states are molecular like states of these hadrons. The five quarks are clustered as $c\bar{c}uud \to (cud)$-$(\bar{c}u)$, and so

$$\begin{aligned}
&P_c^+(4312) \sim \Sigma_c \bar{D} \\
&P_c^+(4440), P_c^+(4457) \sim \Sigma_c \bar{D}^*
\end{aligned} \tag{3}$$

By knowing the spin and parity of $\Sigma_c, \bar{D}, \bar{D}^*$ and assuming that the molecules are in S-wave, their spin and parity are expected to be $1/2^-$ for $P_c^+(4312)$, and $1/2^-$ or $3/2^-$ for $P_c^+(4440), P_c^+(4457)$.

Motivated by these observations, we have started our project in October 2016, when one of the authors Hosaka stayed in Genova and discussed the problem with Santopinto and Yamaguchi who was a postdoc there. Prior to this project we had some experiences of molecular structure of hadrons, with the emphasis on the special role of the pion exchange force at long distances [3, 4]. As shown in the first term of Fig. 3, the pion is exchanged between light quarks $q = u, d$ which are the ingredients of the possible molecular components such as $\Sigma_c \sim cud, \bar{D}^* \sim \bar{c}u$. At the same time we consider the important role of short range interaction where quark dynamics is of direct relevance as shown in the second term of Fig. 3. We have then proposed a model of hadronic molecules with the one pion exchange force and quark dynamics.

This article reports our previous work from 2017 to 2020 which have been performed in collaboration with the group of Genova and several domestic institutions [5, 6]. By this work Yasuhiro Yamaguchi was awarded the JPS prize for young scientists, "Wakate Shorei Sho" in 2021.

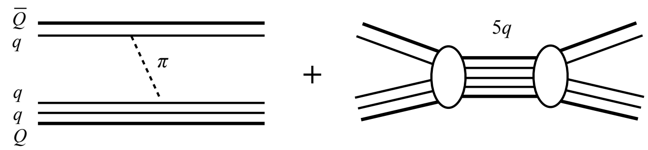

FIG. 3. Interaction between meson and baryon. The first term is due to the pion exchange between light quarks, and the second the coupling of the meson-baryon (MB) states to five quark ($5q$) states.

THEORETICAL METHOD

Our model is a hybrid model of hadronic molecules of mesons and baryons (MB) coupled by five quark states ($5q$). In principle, both of these components are described by five quarks with different cluster correlations. Our assumption is that they are well developed and regarded as good basis states. Thus, our model Hamiltonian is expanded by the open-charm MB and $5q$ channels as

$$H = \begin{pmatrix} H_{MB} & V \\ V^\dagger & H_{5q} \end{pmatrix} = \begin{pmatrix} K_{MB} + V_\pi & V \\ V^\dagger & H_{5q} \end{pmatrix} \tag{4}$$

and the corresponding Schrödinger equation is given by

$$\begin{pmatrix} H_{MB} & V \\ V^\dagger & H_{5q} \end{pmatrix} \begin{pmatrix} \psi_{MB} \\ \psi_{5q} \end{pmatrix} = E \begin{pmatrix} \psi_{MB} \\ \psi_{5q} \end{pmatrix} \tag{5}$$

In the second equation of the Hamiltonian (4) we have shown the OPEP V_π explicitly. Eliminating ψ_{5q} in the coupled equation (5) we obtain the equation for the meson-baryon channel ψ_{MB} which is the direct relevance to the experimental observations,

$$(K_{MB} + V_\pi + U_{eff})\, \psi_{MB} = E \psi_{MB}. \tag{6}$$

where the effective interaction is given by

$$U_{eff} = V_\pi + V \frac{1}{E - H_{5q}} V^\dagger \tag{7}$$

with the corresponding diagram shown in Fig. 3.

Details of the computational method is found in Refs. [5, 6]. Here we list some important ideas.

- The OPEP takes on the form in momentum space, $\boldsymbol{q} = \boldsymbol{p}' - \boldsymbol{p}$,

  $$\begin{aligned} V_\pi(\boldsymbol{q}) = &-\left(\frac{g_A^{\pi MM} g_A^{\pi BB}}{4 f_\pi^2} \right) \\ &\times \frac{(\boldsymbol{S}_1 \cdot \boldsymbol{q})(\boldsymbol{S}_2 \cdot \boldsymbol{q})}{\boldsymbol{q}^2 + m_\pi^2} \hat{\boldsymbol{T}}_1 \cdot \hat{\boldsymbol{T}}_2\,, \end{aligned} \tag{8}$$

  where $g_A^{\pi MM}, g_A^{\pi BB}$ are the axial coupling constants for mesons and baryons, respectively, and $\boldsymbol{S}_{1,2}$ are the spin operators for the relevant hadrons. The axial coupling constants are then determined from the pion-quark coupling by constructing the wave functions of mesons and baryons by the quark model. We note that the resulting coupling constants satisfy the heavy quark symmetry for $\bar{D}^{(*)}$ mesons and $\bar{\Sigma}_c^{(*)}$ baryons. The form factor is also constructed by the quark model wave functions. In this way we can fix all parameters for V_π.

- For the coupling of MB-$5q$, we employ the idea of the spectroscopic factor where we assume that the strength of the MB-$5q$ coupling is proportional to the probability of a MB state at zero distance to meet a $5q$ state. The five quark states are formed by taking into account various color configurations [7]. Thus the relative strength of various MB-$5q$ couplings are fixed.

- Another dynamical issue is the treatment of the non-local term of the effective interaction, the second term of U_{eff}. Observing that the energies of $5q$ states H_{5q} are estimated around $\Delta E \sim 400$ MeV higher than the relevant threshold energy region of MB, we approximate it as a contact term with smeared by the Gaussian type local potential of range 1 fm.

- Finally, one unknown parameter is the overall coupling strength for the MB-$5q$ couplings, f [5, 6]. This is the only one parameter of our hybrid model that can be determined in comparison with data.

In this way, once f is fixed by using one experimental input the interaction strengths are completely determined.

RESULTS AND DISCUSSIONS

Eq. (5) is solved by using variational method. We used the Gaussian basis functions as trial functions [8]. To obtain resonance states, we employed the complex scaling method [9]. In Fig. 4, the results are shown for two f's $f/f_0 = 50$ where $f_0 \sim 6$ MeV [6]. Both experimental data and theory results are shown by rectangular boxes with their middle points corresponding to the masses as indicated by the numbers nearby, and their vertical length decay widths. The boxed numbers are for those states observed by the experiment and the corresponding ones of the model.

For smaller value $f/f_0 = 50$, observed states $P_c(4312)$ and $P_c(4440)$ are well explained not only for their masses but also for decay widths. For $P_c(4457)$, $f/f_0 = 50$ does not hold a resonance, but it may survive as a virtual state. For the larger $f/f_0 = 80$, all states are bound with similar tendency but the levels are lowered due to stronger attraction. These observed states have a dominant components as indicated by Eq. (3).

In addition to the observed states, our model predicts other states near the thresholds; one at around 4350 – 4370 MeV below the $\Sigma_c^* \bar{D}$ threshold, and three scattered around 4470 – 4530 MeV below the $\Sigma_c^* \bar{D}^*$. As expected these states have dominant component of the corresponding threshold particles, forming the heavy-quark multiplets; the doublet of $\Sigma_c \bar{D}^*$ and triplet of $\Sigma_c^* \bar{D}^*$.

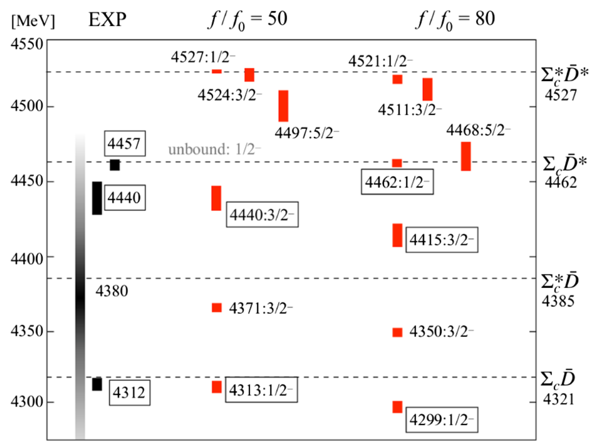

FIG. 4. Experimental data (EXP) [1, 2] and our results of masses and widths for various P_c states [6]. The horizontal dashed lines show the thresholds for corresponding channels and values in the right axis are isospin averaged ones in units of MeV. The centers of the bars are located at the central values of pentaquark masses while their lengths correspond to the pentaquark widths with the exception of $P_c(4380)$ width.

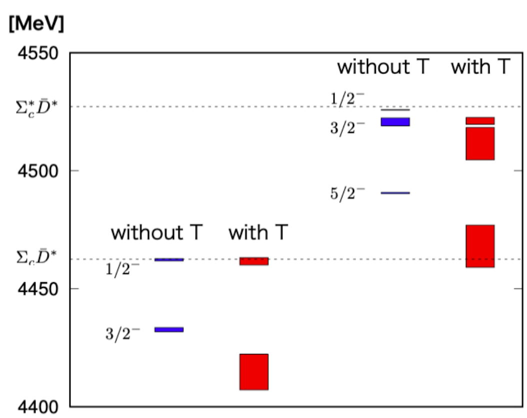

FIG. 5. Comparing the results with and without the tensor force of the OPEP for the states around the $\Sigma_c \bar{D}^*$ and $\Sigma_c^* \bar{D}^*$ thresholds [6]. The label 'without T' stands for the result without the OPEP tensor force, while the label 'with T' stands for that with the OPEP tensor force. The same convention is adopted as in Fig. 4.

Detailed discussions are discussed in Ref. [6]; here we briefly summarize important features.

- The OPEP provides attraction through the tensor force in the second order process. This is the same mechanism as for the deuteron, where only the

OPEP is sufficient to generate the bound states of the binding energy 2 MeV by setting the cutoff parameter in the form factor around 800 MeV which is very consistent with the core size of the nucleon $r_c \sim 0.6 fm$; $\Lambda \sim \sqrt{6} r_c \sim 800$ MeV. In the present case, the OPEP alone does not produce sufficient attraction. The main reason is that the coupling strength is smaller than for the nucleon due to the smaller number of light valence quarks that couple to the pion.

- Another source of attraction is provided by the coupling to the $5q$ states. When their masses are higher than the relevant threshold energies E, the negative denominator $E - M_{5q} < 0$ guarantees the attractive contribution. The strength, however, is not determined theoretically in the present study which was then fixed in comparison with data.

- The level ordering of heavy quark multiplets is dominated by the tensor force of the OPEP. For instance, the larger attraction due to the second order tensor force lowers the $3/2^-$ state of $\Sigma_c \bar{D}^*$ than the $1/2^-$. The same mechanism works for the triplet of $5/2^-, 3/2^-, 1/2^-$ of $\Sigma_c^* \bar{D}^*$. This observation contrasts to other model prediction [10].

- The tensor force due to the OPEP is also important to reproduce the observed widths As shown in Fig. 5 where the results are compared with and without the OPEP, clearly indicating the importance of the OPEP.

Having observed the above features, important conclusion of our present study is the following prediction for the spin and parity identification,

$$P_c(4312) : 1/2^-, \; P_c(4440) : 3/2^-, \; P_c(4457) : 3/2^-$$

where $P_c(4312)$ is a heavy quark spin singlet, and $P_c(4445)$, $P_c(4457)$ form a heavy quark spin doublet. Furthermore, we expect the existence of other states formed by $\Sigma_c^* \bar{D}^*$. At present, their spin and parity are not yet determined experimentally. It is crucial to know the spin and parity of these states as well as the further search for the other states.

Acknowledgments

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