Pc pentaquarks with chiral tensor and quark dynamics

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In recent years, the research on hadrons with unusual structures has been actively conducted. Hadrons are composed of quarks that are a type of elementary particles. The ordinary hadrons can be classified by a baryon consisting of three quarks (qqq) and a meson of quarks-antiquarks ($q\bar{q}$) as shown in Fig. 1(a). The baryon and meson pictures have explained the nature of many hadron states observed in the experiments, e.g. protons and neutrons being uud and udd baryons, respectively, consisting of up (u) and down (d) quarks.

In the recent accelerator experiments, "Exotic hadrons" that cannot be explained by the ordinary hadron picture have been reported. In 2015, the exotic hadron named P_c was reported by the Large Hadron Collider beauty (LHCb) experiment in proton-proton collisions [1]. The P_c state is not classified within the ordinary hadrons, while it is considered to be a $uudc\bar{c}$ five-quark state having a charm (c) and an anti-charm ($\bar{c}$) quarks. Such a state consisting of five quarks is called pentaquark. So far, four pentaquarks $P_c(4312)$, $P_c(4380)$, $P_c(4440)$, and $P_c(4457)$ have been reported [1,2].

The P_c states are assumed to be pentaquarks, but how the five quarks make them up is not understood. In the theoretical studies, the compact five-quark state and hadronic molecule have been discussed (Fig. 1(b)). The compact five-quark state is realized as a compact bound state of the five quarks. The hadronic molecule is a loosely bound state of a meson and baryon, where three of the five quarks in P_c make up the baryon, and the remaining quarks (quark and antiquark) do the meson. The hadronic molecular picture was inspired because the P_c states were found near the thresholds of the $\Sigma_c^{(*)}$baryon and the $\bar{D}^{(*)}$ meson ($\Sigma_c^{(*)} = \Sigma_c, \Sigma_c^*$ and $\bar{D}^{(*)} = \bar{D}, \bar{D}^*$).

In the previous studies, the authors considered models employing either the compact state or hadronic molecule picture. However, the rearrangement of quarks allows the two states to mix. In this study, we introduce the mixture of the compact state in the hadronic molecule and predict masses and decay widths of the pentaquarks. By comparing our results with the LHCb data, we investigate the P_c structures.

The mixture of the compact state is introduced as a short-range force between $\Sigma_c^{(*)}$ and $\bar{D}^{(*)}$ in the hadronic molecule channels. In Ref. [3], we found that this short-range force produces an attraction due to the level repulsion, because the masses of the compact states are larger than those of the $\Sigma_c^{(*)}\bar{D}^{(*)}$ thresholds. We also introduce the one pion exchange potential (OPEP). The tensor term of the OPEP produces an attraction through the coupled channel effects and has been known as the driving force to bind atomic nuclei.

By solving the Schrodinger equations for the $\Sigma_c^{(*)}\bar{D}^{(*)}$ system coupled to the compact five-quark state, we obtain masses and decay widths of the pentaquarks as shown in Fig. 2. Our model predicts three states whose masses and widths are reasonably agreement with those of $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ in the LHCb experiment. The two bars connected by the arrows are the corresponding experimental data and predicted states. These results indicate that the P_c pentaquarks are described as the hybrid states of the compact state and hadronic molecule.

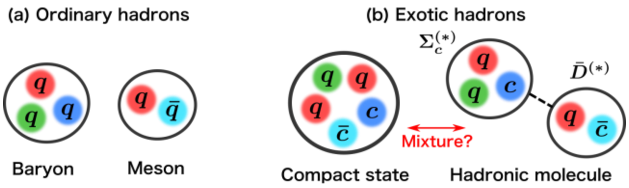

Fig. 1 Ordinary hadrons (baryon and meson) and exotic hadrons (compact state and hadronic molecule). These exotic structures have been considered to be candidates of the structures of $\boldsymbol{P_c}$ pentaquarks.

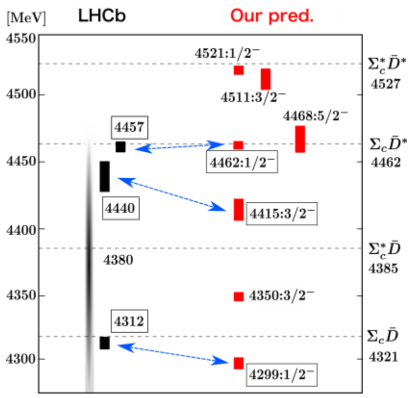

Fig. 2 Experimental data (LHCb) and our predictions of masses and widths of the pentaquarks. A center of the bars are located at the central values of the masses, while their lengths correspond to the decay widths. The horizontal dashed lines show the baryon-meson thresholds. The values are in unit of MeV, taken from [4].

We also obtain the state whose mass is close to the one of $P_c(4380)$. However, the widths are disagreement. Since $P_c(4380)$ has the broad width of about 200 MeV, further theoretical and experimental studies would be necessary to understand that nature.

In addition, our model predicts new three states below the $\Sigma_c^*\bar{D}^*$ threshold, that have not been reported in experiments yet. It is interesting to search for such pentaquark states in the future.

Understanding the exotic structures would lead to the elucidation of the quark confinement that is the fundamental problem how matter in the universe is created from quarks.

References

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