New narrow LHCb pentaquarks as lowest antiquark-diquark-diquark systems

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Abstract

The antiquark-diquark-diquark model describes pentaquark states both in terms of quarks and hadrons. We discuss pentaquark states with hidden charm $P(\bar{c}cuud)$ discovered in the $J/\Psi p$ spectrum by the LHCb collaboration. We consider three pentaquark states as members of the lowest (S-wave) multiplet and discuss the mass splitting scheme. The latest LHCb data for pentaquarks with hidden charm provide an opportunity to make an assumption about the diquark content of the pentaquark states. We give a classification for the LHCb pentaquarks and define recombination channels for these states.

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1 Introduction

The observation of the pentaquark state $P_c(4450)^+$ in the reaction $\Lambda_b \to J/\Psi K^− p$ reported by the LHCb collaboration was one of the most essential issues in the hadron spectroscopy [1]. This state was associated with a relatively narrow peak in the $J/\Psi p$ channel, however the partial wave analysis of the measured data could not identify uniquely it’s quantum numbers. Recently the LHCb collaboration collected the new data and performed the
particle identification analysis. The total statistic was increased by nine times and the detection efficiency of the \( \Lambda_b \) state in the new data set was notably improved. The new analysis showed that the earlier observed signal has a two peak structure and is identified at present as the contribution from the two pentaquark states \( P_c(4440)^+ \) and \( P_c(4457)^+ \) \[2\]. Moreover the new data allowed the collaboration to observe a new state \( P_c(4312) \) which escaped the identification in the low statistic data. However, in spite of the very high statistic of the new data the LHCb collaboration was not able to define the quantum numbers of the observed states.

The nature of the observed states was intensively discussed since the first LHCb report was published. The treatment of pentaquark as a five quark bound state produces a huge numbers of the resonances in the light and heavy quark sector. Therefore it is clear that a pentaquark state should have a configuration with much less degrees of freedom. One of the popular suggestion is that the pentaquark is the baryon-meson molecule state. This idea was discussed in the original LHCb paper (see Ref. \[2\] and references therein) and was based on the observation that the found states are situated near the thresholds of \( \Sigma_c \) hyperons and \( D^* \) mesons. In this case the pentaquarks are loosely bound states with binding energy of few MeV and their decay is defined by the properties of the constituent particles.

Another interpretation is based on the idea that the pentaquarks are bound states of a heavy quarkonium and a light baryon (see Ref. \[3\] and references therein). Such states are called hadroquarkonium and their binding energy is order of the hundred MeV.

The idea which naturally decreases the number of resonances is a formation of diquark states with the \( L = 0 \) orbital momentum between quarks. In this case the pentaquark is a \( \bar{c} \cdot (cu) \cdot (ud) \) bound system (see Refs. \[5, 6, 7, 4, 8\]). In the present paper we also discuss this idea which can naturally explain the observed spectrum. In this case the quantum numbers of the lowest pentaquark state \( P_c(4312)^+ \) should have the \( J^P = 1/2^- \) quantum numbers and the \( P_c(4440)^+ \) and \( P_c(4457)^+ \) states should have spin-parity \( 1/2^- \) and \( 3/2^- \). According to the antiquark-diquark-diquark model all these states are members of the same \( P = \bar{c} \cdot (cu) \cdot (ud) \) multiplet. In the present paper we discuss the possible configuration of the observed states and calculate their recombination transitions. We suppose that this recombination defines the main part of the decay process of the observed states.
2 Color-spin-isospin structure of the pentaquark

With \( L = 0 \) orbital moment two kinds of diquark can be formed: the scalar diquark \( S^{I_z,J_J}_q \) and the axial-vector diquark \( A^{I_z,J_J}_q \). Such diquarks can be formed either between two light quarks \( q_i \) or between the heavy and light quarks:

\[
\begin{align*}
S^{I_z=0,0}_q (I = 1/2, J = 0), & \quad A^{I_z=1,1}_q (I = 1/2, J = 1), \\
S^{0,0}_q (I = 0, J = 0), & \quad A^{1,1}_q (I = 1, J = 1),
\end{align*}
\]

where \( I \) and \( J \) refer to isospin and spin of the diquarks. In terms of these diquarks the color-flavor wave function of pentaquark reads:

\[
P_{\bar{c}c\cdot q_1q_2} = \bar{c}^{\alpha} \cdot \epsilon_{\alpha\beta\gamma} \begin{vmatrix} S^\beta_{q_1} \\ A^\beta_{q_1} \\ S^\gamma_{q_2q_3} \\ A^\gamma_{q_2q_3} \end{vmatrix},
\]

where \( q_i \) refer to light quarks \( u, d \). So, the low-lying \( S \)-wave pentaquark multiplet \( P(I, J^P) \) for isospin \( I = \frac{1}{2} \) reads:

\[
P_{\bar{c}c\cdot(q_1q_2)} = P_{S,c} \left( \frac{1}{2}, \frac{1}{2} \right),
\]

\[
\begin{align*}
P_{S,c} \left( \frac{1}{2}, \frac{1}{2} \right) & \quad P_{S,c} \left( \frac{1}{2}, \frac{3}{2} \right), \\
P_{A,c} \left( \frac{1}{2}, \frac{1}{2} \right) & \quad P_{A,c} \left( \frac{1}{2}, \frac{3}{2} \right), \\
P_{A,c} \left( \frac{1}{2}, \frac{3}{2} \right) & \quad P_{A,c} \left( \frac{1}{2}, \frac{5}{2} \right).
\end{align*}
\]

As we can see the consideration of four diquarks leads to ten pentaquark states. The scalar diquark \( S \) is a "good diquark" in Wilczek and Jaffe’s terminology and has a lower energy than the axial one.

3 Mass splitting scheme

All three observed pentaquarks with hidden charm are relatively narrow states and have a specific mass pattern. The mass splitting and decay rate was discussed in the number of papers [4, 9, 10, 11, 12, 13, 14, 15, 16].

Let us consider the mass splitting scheme for the observed pentaquarks on the basis of the hypothesis about their quark-diquark nature. As it was
shown in Refs. [17, 18, 19] the mass splitting of hadrons can be well described in the framework of the quark model by the short-ranged color-magnetic interactions of the constituents. For mesons and baryons the mass formulae discussed by Glashow are:

\[
M_M = \sum_{j=1,2} m_{q(j)} + a \frac{\vec{s}_1 \vec{s}_2}{m_{q(1)} m_{q(2)}},
\]

\[
M_B = \sum_{j=1,2,3} m_{q(j)} + b \sum_{j>\ell} \frac{\vec{s}_j \vec{s}_\ell}{m_{q(j)} m_{q(\ell)}},
\]

where \(\vec{s}_j\) and \(m_{q(j)}\) refer to spins and masses of the constituents. Mass splitting parameters in Eq. (1) \(a\) and \(b\) are characterized by the size of the color-magnetic interaction and the size of the formed hadrons, the source of the short-range interaction was suggested in Ref. [19]. Initially equations (1) were put forward for the 36-plet of mesons \((q\bar{q})\) and 56-plet of baryons \((qqq)\) and works there very well.

Modified formulae (1) can be naturally applied to the pentaquark systems. For multiquark states from Ref. [2] we have:

\[
M_{q_1q_2q_3c\bar{c}} = m_{D(q_1q_2)D(q_3c)} + 4\Delta \left( \vec{\mu}_{D(q_1q_2)} \vec{\mu}_{D(q_3)} + \vec{\mu}_{D(q_1q_2)} \vec{\mu}_{D(q_3)} + \vec{\mu}_{D(q_3)} \vec{\mu}_{D(q_1q_2)} \right)
\]

\[
m_{D(q_1q_2)D(q_3c)} = m_{D(q_1q_2)} + m_{D(q_3)} + m_{\bar{c}}
\]

where \(\vec{\mu}_D\) and \(\vec{\mu}_{\bar{c}}\) are color-magnetic moments of diquarks and \(c\)-quark, \(\Delta\) is the parameter of spin splitting. Diquarks are considered as composite systems of quarks analogous to light nuclei. The magnetic moments are written as sums of quark magnetic moments:

\[
\vec{\mu}_{D(q_1q_2)} = \vec{s}_q \frac{m_q}{m_q} + \vec{s}_{\bar{q}} \frac{m_{\bar{q}}}{m_{\bar{q}}}, \quad \vec{\mu}_{D(q_3c)} = \vec{s}_q \frac{m_q}{m_q} + \vec{s}_c \frac{m_c}{m_c} \approx \vec{s}_q \frac{m_c}{m_q},
\]

\[
\vec{\mu}_{\bar{c}} = \frac{\vec{s}_c}{m_c} \approx 0.
\]

Here we take into account that \(m_c \gg m_q\).

### 3.1 Estimation of diquark and pentaquark masses

Estimation of diquark masses is the most problematic issue in the study of diquarks (see for example Ref. [20]). Basing on Refs. [21], [22] we estimate
the masses of scalar $S$ ($J^P = 0^+$) and axial $A$ ($J^P = 1^+$) diquarks as follows (in MeV units).

$$
m_q = 330, \quad m_c = 1450,
m_{S(q_1q_2)} = 750, \quad m_{S(qqc)} = 2100,
m_{A(q_1q_2)} = 850, \quad m_{A(qqc)} = 2200.
$$

Here we explore the most general pattern with existence of the axial diquark between heavy and the light quarks.

As it would be discussed below it is natural to consider for LHCb pentaquarks two configurations: the first one consisting of two scalar diquarks $P_c = \bar{c}S_cS$ and the second one consisting of one scalar and one axial diquark $P_c = \bar{c}S_cA$, $P_c = \bar{c}A_cS$. Then in the mass region below 4500 MeV we obtain the five states with following masses:

| $P^{(L,J^P)}_{DD,\bar{c}}$ | mass MeV |
|--------------------------|----------|
| $P_{SS,\bar{c}}^{(0,\frac{1}{2})}$ | $m_{SS,\bar{c}} \simeq 4300$ |
| $P_{AS,\bar{c}}^{(1,\frac{1}{2})}$ | $m_{AS,\bar{c}} \simeq 4400$ |
| $P_{AS,\bar{c}}^{(1,\frac{3}{2}^-)}$ | $m_{AS,\bar{c}} \simeq 4400$ |
| $P_{SA,\bar{c}}^{(1,\frac{1}{2})}$ | $m_{SA,\bar{c}} \simeq 4400$ |
| $P_{SA,\bar{c}}^{(1,\frac{3}{2}^-)}$ | $m_{SA,\bar{c}} \simeq 4400$ |

Really in the Glashow formulae the coordinate part of the wave function is hidden in parameters $a$ and $b$. They may be different for standard and exotic hadrons. Therefore we should emphasize that all our mass estimations are only qualitative ones.

## 4 Production mechanism for LHCb pentaquarks

The diquark picture suggests five states in the mass region below 4500 MeV. The pentaquarks which formed by the two axial diquarks should have masses in the region 4600 MeV. However in a particular reaction some of the states can be forbidden (or have a very small probability) due to the production mechanism. The LHCb pentaquark states were observed in the decay of the $\Lambda_b$ meson into $J/\Psi K^-p$ system. Such decay is defined by the weak transition of the $b$ quark into $c\bar{c}s$ system. The $\Lambda_b$ is formed by the heavy $b$ quark and
the light scalar diquark and it is natural to suggest that this diquark forms the final pentaquark states. In this case we expect that only three states can be observed in the reaction $\Lambda_b \to J/\Psi K^- p$: $P_{SS,\bar{c}\bar{c}}^{(0,\frac{1}{2}^{-})}$, $P_{SA,\bar{c}\bar{c}}^{(1,\frac{1}{2}^{-})}$ and $P_{SA,\bar{c}\bar{c}}^{(1,\frac{3}{2}^{-})}$. The pentaquark with heavy axial diquark should be produced in the decay of the $\Sigma_b$ particle. However this is a very rare event due to dominant decay of the $\Sigma_b$ baryon into $\Lambda_b \pi$ system. Possibly this state can be seen in the reaction of the proton-antiproton annihilation which will be studied by the PANDA experiment.

5 Recombination channels

Let us present the recombination scheme for the discussed pentaquarks. We use the notation $P^{I,I_z,J,J_z}$, where $I$ and $J$ refer to isospin and spin of the pentaquark correspondingly.

For the combination $P = \bar{c}S_{cu} \cdot S_{ud}$ we obtain the following recombination scheme:

$$P_{\bar{c}S_{cu} \cdot S_{ud}}^{\frac{1}{2}+\frac{1}{2}} = -\frac{1}{2} J/\Psi^{\uparrow} (p^\uparrow + p'^\uparrow) + \frac{1}{2} (\bar{D}^{*0}(0) - \bar{D}^{0}) \Lambda_c^{+\uparrow} +$$

$$+ \frac{1}{2\sqrt{2}} (J/\Psi^{(0)} - \eta_c) (p^\uparrow + p'^\uparrow) - \frac{1}{\sqrt{2}} \bar{D}^{*0\uparrow} \Lambda_c^{+\downarrow}. \quad (9)$$

Here $p'$ is some radial excitation of proton. In the mass region of the observed pentaquarks the open channels are $J/\Psi p$, $D^0 \Lambda_c$ and $\eta_c p$. Therefore the lowest mass state $P_c(4312)^+$ should be also seen in the $D^0 \Lambda_c$ and $\eta_c p$ channels. However the production rate in these channels will be suppressed compare to the $J/\Psi p$ channel by the factors 0.6 and 0.4 correspondingly.

For the case of the axial diquark formed by the heavy and light quark and the scalar light diquark we have the following result:

$$P_{\bar{c}A(\bar{c}u)S_{ud}}^{\frac{1}{2}+\frac{1}{2}+\frac{1}{2}+\frac{1}{2}} = -\frac{1}{\sqrt{6}} (J/\Psi^{(0)} + \eta_c) (p^\uparrow + p'^\uparrow) + \frac{1}{\sqrt{3}} (\bar{D}^{*0(0)} + D^{0}) \Lambda_c^{+\uparrow} +$$

$$+ \frac{1}{\sqrt{12}} J/\Psi^{\uparrow} (p^\uparrow + p'^\uparrow) - \frac{1}{\sqrt{12}} (\bar{D}^{*0(0)} - D^{0}) \Lambda_c^{+\uparrow} +$$

$$+ \frac{1}{2\sqrt{6}} (J/\Psi^{(0)} - \eta_c) (p^\uparrow + p'^\uparrow) - \frac{1}{\sqrt{6}} \bar{D}^{*0\uparrow} \Lambda_c^{+\downarrow}. \quad (10)$$

$$P_{\bar{c}A(\bar{c}u)S_{ud}}^{\frac{1}{2}+\frac{1}{2}+\frac{1}{2}+\frac{1}{2}} = -\frac{1}{\sqrt{2}} J/\Psi^{\uparrow} (p^\uparrow + p'^\uparrow) + \bar{D}^{*0\uparrow} \Lambda_c^{+\downarrow}. \quad (11)$$
The state with quantum numbers $J^P = 3/2^-$ does not decay into the $D^0 \Lambda_c$ and $\eta_c p$ final states in the S-wave. It can decay into these channels in the D-wave, however such production should be heavily suppressed by the small phase volume.

The production rate of the high mass $1/2^-$ state will be by the factor 5.3 larger for the $D^0 \Lambda_c$ decay channel and by the factor 3.6 larger for the $\eta_c p$ channel compare to the $J/\psi p$ channel. It means that in the $D^0 \Lambda_c$ and $\eta_c p$ final states only two signals from the $J^P = 1/2^-$ resonances will be observed and the signal from the high mass state is expected to be by almost 10 times stronger.

For the combination $P = \bar{c} S_{cu} \cdot A_{ud}$ we have:

$$P_{\bar{c} S_{cu} A_{ud}} = \frac{-\sqrt{2}}{3} J/\psi (0) N^{\frac{1}{2} + \frac{3}{2}} - \frac{\sqrt{2}}{12} J/\psi (0) p^+ +$$
$$+ \frac{\sqrt{2}}{12} J/\psi (0) p^+ + \eta_c p^+ + \sqrt{3} J/\psi (0) p^- +$$
$$+ \frac{1}{3} J/\psi (0) p^+ - \frac{1}{6} J/\psi (0) p^- - \frac{\sqrt{2}}{4} \eta_c p^+ -$$
$$- \frac{\sqrt{6}}{18} D^0 \Sigma_c^{+10, 0} - \frac{1}{3} D^0 \tilde{\Sigma}_c^{+10, \frac{3}{2}} + \frac{\sqrt{3}}{18} D^0 \sum^{+10, \frac{3}{2}} +$$
$$+ \frac{\sqrt{3}}{6} D^0 \Sigma_c^{+10, \frac{3}{2}} - \frac{\sqrt{6}}{9} D^0 \tilde{\Sigma}_c^{+10, 0} + \frac{\sqrt{6}}{9} D^0 \sum^{+10, \frac{3}{2}} +$$
$$+ \frac{\sqrt{3}}{9} D^0 \Sigma_c^{+10, 0} - \frac{\sqrt{6}}{6} D^0 \tilde{\Sigma}_c^{+10, \frac{3}{2}} -$$
$$- \frac{\sqrt{6}}{18} D^0 \sum^{+10, \frac{3}{2}} + \frac{\sqrt{6}}{9} D^0 \Sigma_c^{+10, \frac{3}{2}} +$$
$$- \frac{2 \sqrt{3}}{9} D^0 \sum^{+10, \frac{3}{2}} + \frac{\sqrt{2}}{3} D^0 \Sigma_c^{+10, \frac{3}{2}}. \quad (12)$$

Here the baryon $N^{\frac{1}{2} + \frac{3}{2}}_{J^P}$ is the well known $N(1520)3/2^-$. For the pentaquark states with spin and its projection $J J_z = \frac{3}{2} \frac{3}{2}$ we obtain:

$$P_{\bar{c} S_{cu} A_{ud}} = \frac{1}{6} [3(J/\psi (0) - \eta_c) N^{\frac{1}{2} + \frac{3}{2}} - \sqrt{6} J/\psi (0) N^{\frac{1}{2} + \frac{3}{2}} + p^+ - p^+ +$$
$$+ \tilde{D}^0 \sum^{+10, \frac{3}{2}} + \sqrt{2} \tilde{\Sigma}_c^{+10, \frac{3}{2}} - \sqrt{3} (D^0 - \tilde{D}^0) \Sigma_c^{+10, \frac{3}{2}} -$$
$$- 2D^0 (\sqrt{2} \Sigma_c^{+10, \frac{3}{2}} - \Sigma_c^{+10, \frac{3}{2}}) + \sqrt{6} (D^0 - \tilde{D}^0) \Sigma_c^{+10, \frac{3}{2}}], \quad (13)$$
\[
P_{c\Lambda_c(Sud)} = -\frac{1}{\sqrt{2}} J/\Psi (p^+ + p'^+) + D^{*0}\Lambda_c^{+00}. \tag{14}
\]

As we can see such states can be observed from their decay into \( J/\Psi p \) and \( \eta_c p \) channels. However the states with the axial light diquark should be produced from the decay of the \( \Sigma_b \) state, where the weak decay is strongly suppressed by the strong decay into the \( \Lambda_b \pi \) channel.

### 6 Conclusion

We discuss the description of three LHCb pentaquarks in terms of diquark-diquark-antiquark model. Basing on the idea that the light scalar diquark which forms initial \( \Lambda_b \) state directly participates in the formation of the final pentaquark state we reproduce the mass spectrum observed by the LHCb collaboration. The lowest LHCb state \( P_c^+(4312) \) is formed by scalar diquarks and has the structure \( P = \bar{c}S_{cu} \cdot S_{ud} \) with quantum numbers \( I, J^P = 1/2, 1/2^- \). The two states \( P_c^+(4440) \) and \( P_c^+(4457) \) are formed by the axial heavy diquark and the light scalar diquark and have quantum numbers \( I, J^P = 1/2, 1/2^- \) and \( I, J^P = 1/2, 3/2^- \). The states with quantum numbers \( I, J^P = 1/2, 1/2^- \) can be also observed in the \( D^0\Lambda_c \) and \( \eta_c p \) decay channels. Here the production rate of the lowest mass state into these channels will be suppressed by the factors 0.6 and 0.4 (compare to the decay rate into \( J/\Psi p \)) while the production rate of the high mass state will be increased by the factors 5.3 and 3.6 correspondingly.

The pentaquark states with the axial scalar diquark can be produced form the weak decay of the \( \Sigma_b \) state. However such reaction has a very small decay rate due to possibility of the \( \Sigma_b \) meson to decay strongly into the \( \Lambda_b \pi \) state. One of the possible sources to observe such states is the proton-antiproton annihilation reaction or the \( \gamma p \) collision data.

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