Pentaquarks and resonances in the $pJ/\psi$ spectrum

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Abstract

We consider exotic baryons with hidden charm as antiquark-diquark-diquark composite systems. Spin and isospin structure of such exotic states is given and masses are estimated. The data for production of pentaquarks in the reaction $\Lambda_b \rightarrow K^- p J/\psi$ are discussed. We suggest that the narrow peak in $pJ/\psi$ spectra at 4450 MeV is antiquark-diquark-diquark state with negative parity, $5/2^-(4450)$, while the broad bump $3/2^+(4380)$ is the result of rescatterings in the $(pJ/\psi)$-channel. Positions of other pentaquarks with negative parity are estimated.

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1 Introduction

Data for the decay $\Lambda_b^0 \rightarrow p J/\psi K^-$ [1] provide a definite argument for the existence of a pentaquark, a baryon system in $pJ/\psi$ spectra which has the following quark content:

$$P_{\bar{c}uud}^+ = \bar{c}(cuud).$$

In terms of the quark-diquark states it can be presented as a three-body systems:

$$\bar{c}(cuud) = \bar{c} \cdot (cu) \cdot (ud) + \text{permutations of the } u,d \text{ quarks}.$$ (2)

A diquark is a color triplet member, similar to a quark, and the right-hand side of eq. (2) presents a three-body system with a color structure similar to that in low-lying baryons. It is reasonable to suppose that we face similar color forces in three quark and antiquark-diquark-diquark systems as well. Following this idea we perform a classification of such baryon states and give estimations of their masses. Estimation of diquark masses is given in [2] where diquark-antidiquark states are studied.
The notion of the diquark was introduced by Gell-Mann [3]. Diquarks were discussed for baryon states during a long time, see pioneering papers [4, 5, 6, 7, 8] and conference presentations [9, 10, 11]. The systematization of baryons in terms of the quark-diquark states is presented in [12, 13]. The application of the diquarks to exotic mesons in the sector of heavy diquarks was discussed by Maiani et al. [14], Voloshin [15], Ali et al. [16].

Pentaquarks built of light-light and light-heavy diquarks present natural extension of multiquark schemes studied in the last decade for mesons [17, 18] and baryons [19, 20].

2 Pentaquarks

In color space we write for the pentaquark:

\[ P_{ccudd}^+ = \epsilon_{\alpha\beta\gamma} \epsilon^\alpha (cu)^\beta (ud)^\gamma \text{ + permutations of the } u, d \text{ quarks} \]

\[ (cu)^\beta = \epsilon^{\beta\beta'\gamma'} c_{\beta'} u_{\gamma'} \]

\[ (ud)^\gamma = \epsilon^{\gamma\beta\gamma''} u_{\beta''} d_{\gamma''} \]

where \( \alpha, \beta, \gamma \) refer to color indices.

We discuss a scheme in which the exotic baryon states are formed by standard QCD-motivated interactions (gluonic exchanges, confinement forces) but in addition with diquarks as constituents.

2.1 Spin structure of the pentaquarks

We work with two diquarks: scalar \( S \) and axial-vector \( A \). In terms of these diquarks the color-flavor wave function of pentaquark reads:

\[ P_{c(cq)-(q'q'')} = \epsilon^\alpha \cdot \epsilon_{\alpha\beta\gamma} S^\beta_{(cq)} S^{\gamma}_{(q'q'')} \]

We have six diquark-diquark states:

\[ P_{c(cq)-(q'q'')} = \epsilon^\alpha \cdot \begin{vmatrix} (S_{(cq)} S_{(q'q'')})^\alpha (0^+) \\ (S_{(cq)} A_{(q'q'')})^\alpha (1^+) \\ (A_{(cq)} S_{(q'q'')})^\alpha (1^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha (0^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha (1^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha (2^+) \end{vmatrix} \]

with the spin-parity numbers \( J^P = 0^+, 1^+, 2^+ \).

2.2 Isospin structure of the diquarks

We face the following isospin states for the diquarks:

\[ S_{(cq)} (I_d = 1/2, J_d = 0), \quad A_{(cq)} (I_d = 1/2, J_d = 1), \]

\[ S_{(q'q'')} (I_d = 0, J_d = 0), \quad A_{(q'q'')} (I_d = 1, J_d = 1). \]
Here we concentrate our attention on non-strange diquarks only, for an expansion of the results of Section 2.3. We write

\[
\begin{bmatrix}
(S_{(cq)}S_{(q'q'')})_\alpha(0^+) \\
(S_{(cq)}A_{(q'q'')})_\alpha(1^+) \\
(A_{(cq)}S_{(q'q'')})_\alpha(1^+) \\
(A_{(cq)}A_{(q'q'')})_\alpha(0^+) \\
(A_{(cq)}A_{(q'q'')})_\alpha(1^+) \\
(A_{(cq)}A_{(q'q'')})_\alpha(2^+)
\end{bmatrix} \rightarrow
\begin{bmatrix}
P_{\frac{1}{2}}^{(\frac{1}{2}, \frac{1}{2})} \\
P_{\frac{3}{2}}^{(\frac{1}{2}, \frac{3}{2})} \\
P_{\frac{3}{2}}^{(\frac{3}{2}, \frac{3}{2})} \\
P_{\frac{5}{2}}^{(\frac{1}{2}, \frac{5}{2})} \\
P_{\frac{5}{2}}^{(\frac{3}{2}, \frac{5}{2})} \\
P_{\frac{5}{2}}^{(\frac{5}{2}, \frac{5}{2})}
\end{bmatrix}
\]

(7)

### 2.3 Pentaquarks, their masses and spins

Mass formula for a diquark-diquark system \((cq) \cdot (q'q'')\), is accepted to be the same as for the diquark-antidiquark one \([2]\). We write

\[
M_{(cq)\cdot(q'q'')} = m_{(cq)} + m_{(q'q'')} + J_{(cq)\cdot(q'q'')} (J_{(cq)\cdot(q'q'')} + 1) \Delta
\]

with the parameters which were determined in ref. \([2]\):

\[
\Delta = 70 \pm 10 \text{ MeV},
m_{S_{(cq)}} = 2000 \pm 50 \text{ MeV}, \quad m_{A_{(cq)}} = 2050 \pm 50 \text{ MeV}.
\]

Here we concentrate our attention on non-strange diquarks only, for an expansion of the results to the strange quark sector we need \(m_{S_{(cq)}}\) and \(m_{A_{(cq)}}\).

For the \((q'q'')\) diquarks we accept masses found in the analysis of baryons \([12, 13]\):

\[
m_{S_{(q'q'')}} = 650 \pm 50 \text{ MeV}, \quad m_{A_{(q'q'')}} = 750 \pm 50 \text{ MeV}.
\]

The mass of the constituent antiquark \(\bar{c}\) is equal to \([21, 22]\):

\[
m_{\bar{c}} = 1300 \pm 50 \text{ MeV}.
\]

Within these masses \([9, 10, 11]\) we roughly estimate the masses of the pentaquarks as:

\[
M_{\bar{c}(cq)\cdot(q'q'')} \simeq m_{\bar{c}} + M_{(cq)\cdot(q'q'')}.
\]

Correspondingly we write a set of the low-laying pentaquark states:

\[
\begin{array}{c|c|c}
\text{I = 1/2} & \text{I = 3/2} \\
\hline
P_{\bar{c}S_{(cq)}S_{(q'q'')}}(3800), & P_{\bar{c}S_{(cq)}A_{(q'q'')}}(4190), & P_{\bar{c}S_{(cq)}A_{(q'q'')}}(4190),
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{I = 1/2} & \text{I = 3/2} \\
\hline
P_{\bar{c}A_{(cq)}S_{(q'q'')}}(4140), & P_{\bar{c}A_{(cq)}S_{(q'q'')}}(4140), & P_{\bar{c}S_{(cq)}A_{(q'q'')}}(4190),
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{I = 1/2} & \text{I = 3/2} \\
\hline
P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4110), & P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4110), & P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4190),
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{I = 1/2} & \text{I = 3/2} \\
\hline
P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4240), & P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4240), & P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4240),
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{I = 1/2} & \text{I = 3/2} \\
\hline
P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4520), & P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4520), & P_{\bar{c}A_{(cq)}A_{(q'q'')}}(4520),
\end{array}
\]

Masses are given in MeV units, an uncertainty in the determination of masses is of the order of \(\pm 150\) MeV.
3 Discussion

The state $P_{c}^{1/2^{-}}(4520 \pm 150)$ is a good candidate to be a state which was observed in [1]: $5/2^{+}(4450 \pm 4)$ with a width of $\Gamma = 39 \pm 24$ MeV. Then the broad state, $3/2^{+}(3380 \pm 38)$ with $\Gamma = 205 \pm 94$ MeV also observed in the $pJ/\psi$ spectrum, is a positive parity state, $3/2^{+}$.

An opposite classification of states is suggested in [23]: $3/2^{+}(3380 \pm 38) \rightarrow 3/2^{-} (S\text{-wave pentaquark})$ and $5/2^{+}(4450 \pm 4) \rightarrow 5/2^{+} (P\text{-wave pentaquark})$.

We suppose that the broad bump in the $3/2^{+}$-wave is the result of rescatterings in $pJ/\psi$-channel, for example, such as $\Lambda_{b} \rightarrow \Lambda(1520)J/\psi \rightarrow K^{-}(pJ/\psi)$.

In the suggested scheme the mass interval $(4040 - 4500)$ MeV should contain additionally several resonances with $J^{P} = 1/2^{-}, 3/2^{-}$. Some of them may dominantly decay into $p\eta_{c}$-channel, concerning mainly the $1/2^{-}$ states.

The masses of pentaquarks with strange diquarks ($cs$), see eq.(9), are estimated quite similar to the non-strange ones.

In conclusion, the scheme of the low-lying pentaquark is suggested on the basis of the study of the tetraquark states [2]. We are convinced that the crossing studies of exotic mesons and baryons give a correct way for investigation of these topics.

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