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The new pentaquarks in the diquark model



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ABSTRACT

Pentaquark baryons are a natural expectation of an extended picture of hadrons where quarks and diquarks are the fundamental units. The parity/mass pattern observed, when compared to that of exotic mesons, appears as the footprint of a compact five-quark structure. What has been learned from the X , Y , Z phenomenology informs about the newly found pentaquark structure and suggests further experimental tests and directions to be explored.

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1. Introduction

The LHCb Collaboration has reported observation of two new resonances in the Λ_b decay [1],

$$\Lambda_b(bud) \rightarrow \mathbb{P}^+ K^- \quad (1)$$

each decaying according to

$$\mathbb{P}^+ \rightarrow J/\Psi + p \quad (2)$$

Thus the new particles carry a unit of baryonic number and feature the valence quark composition

$$\mathbb{P}^+ = \bar{c}cuud \quad (3)$$

whence the name pentaquarks.

The best fit quantum numbers and masses are¹

$$J^P = 3/2^-, M \simeq 4380 \text{ GeV, fract.} \simeq 8.4\%$$

$$J^P = 5/2^+, M \simeq 4450 \text{ GeV, fract.} \simeq 4.1\% \quad (4)$$

In this note, we comment on the two pentaquarks as the logical extension of the picture already proposed in [2], and for the beauty sector in [3], for the exotic mesons, X , Y , Z , whereby the latter particles are described using diquarks as colored subunits, bound by QCD color forces. See also the discussions in [4].

Light scalar mesons as four quark states have been considered in [5] and further studied in [6,7]. Heavy–light diquarks as building blocks of hidden charm or beauty exotic mesons have been

introduced in [2,3]. Pentaquarks from light diquarks are described in [8,9] see also [10]. Hidden charm pentaquarks were anticipated in [11].

In the particular case of the newly discovered pentaquarks, we are led to identify the basic (color $\bar{\mathbf{3}}$) units as: the charm antiquark \bar{c} , one heavy–light diquark, $[cq]$, and one light–light diquark, $[q'q'']$ (q, q', q'' denote light quarks, which we restrict at first to be the u, d quarks, extending later to the flavor SU(3) triplet, u, d, s).

Needless to say, the picture of colored sub-units opens the door to a rich spectroscopy of states, including orbital excitations in addition to S -wave states, not dissimilar from the baryon spectrum, with the **56** positive parity baryons followed by the **70**, $L = 1$ multiplet of negative parity baryons.

A precise description of pentaquark spectroscopy has to wait for more particles to be identified. However, we shall see that even the two states just observed carry enough information to corroborate the diquark role in the new baryons and mesons and lead to identify some crucial experimental signature that could make decisive progress in this matter.

2. Pentaquark parity

Light, S -wave mesons have negative parity, being made by a quark–antiquark pair whose components have opposite parity. Negative parity is followed by positive parity states ($A_{1,2}$, χ_J states, etc.) due to the excitation of one unit of orbital angular momentum. The negative parity of the lighter state in (4) reflects just the presence of one valence antiquark in (3) and the positive parity of the next state is naturally interpreted as the opening of the orbital, $L = 1$, excitation. Parity ordering in the baryons, that we have just recalled, and in X , Y , Z mesons, is just the op-

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¹ We refer to the original article [1] for experimental errors and more details.

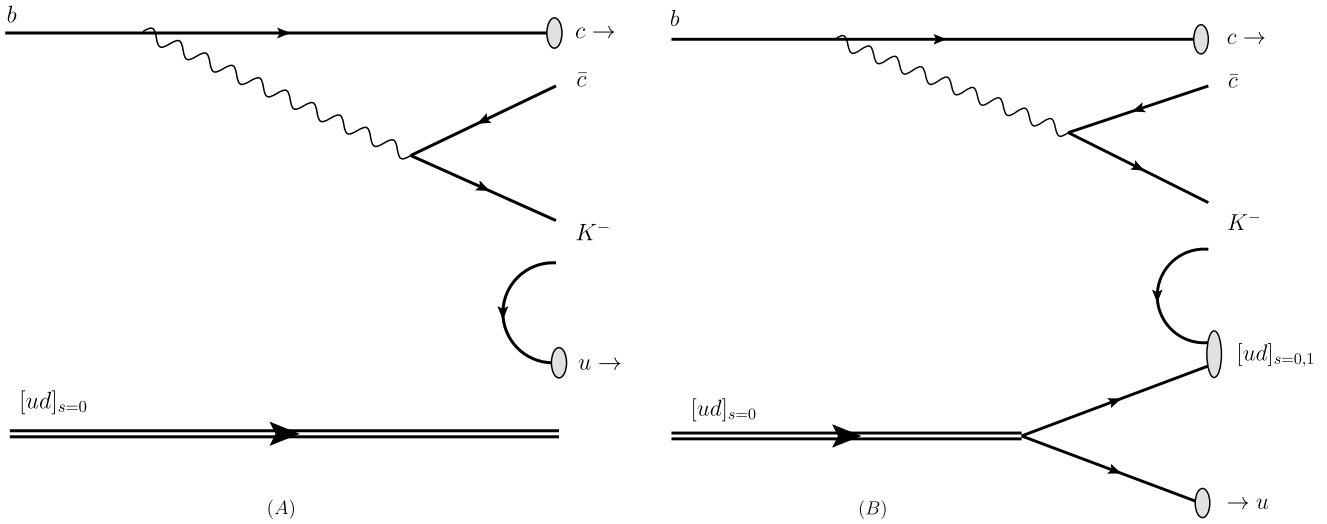


Fig. 1. (A): The $[ud]$, spin zero diquark in the Λ_b is transmitted to the \mathbb{P}_u type pentaquark. (B) The u quark from the vacuum participates in the formation of the light–light diquark: spin zero and one are both permitted. Mechanism (B) may also produce a $[uu]_{s=1}$ diquark, giving rise to the \mathbb{P}_d type pentaquark, Eq. (7).

posite, the $X(3872)$ with $J^{PC} = 1^{++}$, being lighter than $Y(4260)$, with $J^{PC} = 1^{--}$. This feature, of course, reflects the fact that there are no valence antiquarks in the familiar baryons and two quark–antiquark pairs in the lowest lying X , Z mesons, as required by the tetraquark picture.

3. The mass difference

At first sight, the near 70 MeV difference between the masses in (4) does not go well with the energy associated with orbital excitation. One orbital excitation in mesons and baryons carries an energy difference which is typically of order 300 MeV, as exemplified by the mass difference in $\Lambda(1405) - \Lambda(1116) \sim 290$ MeV. Mass formulae for the orbital excitation in X , Y , Z mesons are discussed in [12] and the associated energy difference is estimated to be $\Delta M(L=0 \rightarrow 1) \sim 280$ MeV.

However, the mass difference between light–light diquarks with spin $s=1,0$ [13], estimated from charm and beauty baryon spectra, is of order 200 MeV, e.g. $\Sigma_c(2455) - \Lambda_c(2286) \simeq 170$ MeV, $\Sigma_b(5811) - \Lambda_b(5620) \simeq 190$ MeV.

If we assume the compositions

$$\begin{aligned} \mathbb{P}(3/2^-) &= \{\bar{c}[cq]_{s=1}[q'q']_{s=1}, L=0\} \\ \mathbb{P}(5/2^+) &= \{\bar{c}[cq]_{s=1}[q'q']_{s=0}, L=1\} \end{aligned} \quad (5)$$

the orbital gap is reduced to about 100 MeV, which brings it back to the range of spin–spin and spin–orbit corrections indicated by (4).

Spin one light–light diquarks (Jaffe’s bad diquarks [10]), while conspicuously absent in light meson spectroscopy, are well established in baryons as indicated by the $\Sigma - \Lambda$ mass difference [13] and confirmed by $\Sigma_{c,b} - \Lambda_{c,b}$ mass differences [2].

Concerning the production of a spin 1, light–light $[ud]$ diquark in Λ_b decay, we note that there are in fact two possible mechanisms leading to the pentaquark production, see Fig. 1. In the first one (diagram A in Fig. 1) the b -quark spin is shared between the kaon and the \bar{c} and $[cu]$ components. Barring angular momentum transfer due to gluon exchanges between the light diquark and light quarks from the vacuum, the final $[ud]$ diquark has to have spin zero. In the second mechanism, however (diagram B), the $[ud]$ diquark is formed from the original d quark and the u quark from the vacuum. Angular momentum is shared among all final com-

ponents and the $[ud]$ diquark may well have spin one. The two possibilities are considered in the following discussion.

Concerning heavy quark spin conservation, one can also show that both $\mathbb{P}(3/2^-)$ and $\mathbb{P}(5/2^+)$, as described in (5), have components with $s_{\bar{c}\bar{c}} = 1$. This can be seen by direct inspection or with an SU(2) tensor analysis. HQS conservation in pentaquark decay allows the production of J/Ψ in the final state, as observed.

4. Flavor SU(3) structure of pentaquarks

Pentaquarks realizing the valence quark structure (3) are of two types

$$\mathbb{P}_u = \epsilon^{\alpha\beta\gamma} \bar{c}_\alpha [cu]_{\beta,s=0,1} [ud]_{\gamma,s=0,1} \quad (6)$$

$$\mathbb{P}_d = \epsilon^{\alpha\beta\gamma} \bar{c}_\alpha [cd]_{\beta,s=0,1} [uu]_{\gamma,s=1} \quad (7)$$

where Greek indices are for color, diquarks are in the color antisymmetric, $\bar{\mathbf{3}}$, configuration and overall antisymmetry requires flavor symmetric light–light diquark with $s=1$.

Extending to flavor SU(3), we have two distinct series of pentaquarks according the light–light diquark symmetry

$$\begin{aligned} \mathbb{P}_A &= \epsilon^{\alpha\beta\gamma} \{\bar{c}_\alpha [cq]_{\beta,s=0,1} [q'q']_{\gamma,s=0}, L\} \\ &= \mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8} \end{aligned} \quad (8)$$

$$\begin{aligned} \mathbb{P}_S &= \epsilon^{\alpha\beta\gamma} \{\bar{c}_\alpha [cq]_{\beta,s=0,1} [q'q']_{\gamma,s=1}, L\} \\ &= \mathbf{3} \otimes \mathbf{6} = \mathbf{8} \oplus \mathbf{10} \end{aligned} \quad (9)$$

For S -waves, the first and the second series give the angular momenta

$$\mathbb{P}_A(L=0): J = 1/2 (2), 3/2 (1) \quad (10)$$

$$\mathbb{P}_S(L=0): J = 1/2 (3), 3/2 (3), 5/2 (1) \quad (11)$$

(in parenthesis the multiplicity of each spin value). In consideration of (5), we propose to assign the $3/2^-$ and the $5/2^+$ states to the symmetric and antisymmetric series, respectively.

To study the flavor properties of pentaquark production and decay, we recall that

$$\Lambda_b(bud) \sim \bar{\mathbf{3}} \quad (12)$$

with respect to flavor SU(3) and is isosinglet $I = 0$. The weak non-leptonic Hamiltonian for b decay is²

$$H_w^{(3)}(\Delta I = 0, \Delta S = -1) \quad (13)$$

Therefore, denoting by M a nonet light meson, the weak transition amplitude

$$\langle \mathbb{P}, M | H_w | \Lambda_b \rangle \quad (14)$$

requires $\mathbb{P} + M$ to be in the $\mathbf{8} \oplus \mathbf{1}$ representation. Recalling the well-known SU(3) formulae

$$\begin{aligned} \mathbf{8} \otimes \mathbf{8} &= \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27} \\ \mathbf{8} \otimes \mathbf{10} &= \mathbf{8} \oplus \mathbf{10} \oplus \mathbf{27} \oplus \mathbf{35} \end{aligned} \quad (15)$$

we see that the decay (14) can be realized with \mathbb{P} in either octet or decuplet. The first case is exemplified in Eqs. (1) and (2). However, decays such as

$$\begin{aligned} \Lambda_b &\rightarrow \pi \mathbb{P}_{\mathbf{10}}^{S=-1} \rightarrow \pi (J/\Psi \Sigma(1385)) \\ \Lambda_b &\rightarrow K^+ \mathbb{P}_{\mathbf{10}}^{S=-2} \rightarrow K^+ (J/\Psi \Xi^-(1530)) \end{aligned} \quad (16)$$

might also occur when the $[ud]$ diquark shell in the initial state gets broken in the decay (see B in Fig. 1).

The $\Xi_b^0(bus)$, $\Xi^-(bds)$ and $\Omega_b(bss)$ particles undergo visible weak decays. Example of weak decays from bottom strange baryons involving pentaquarks in the $\mathbf{10}$ and respecting $\Delta I = 0$ and $\Delta S = -1$ is

$$\Xi_b(5794) \rightarrow K (J/\Psi \Sigma(1385)) \quad (17)$$

in various charge combinations, which would correspond to the formation of the pentaquarks

$$\mathbb{P}_{\mathbf{10}}(\bar{c} [cq]_{s=0,1} [q's]_{s=0,1}) \quad (18)$$

with $q, q' = u, d$. The $[ss]$ pair in Ω_b is in pure $\mathbf{6}$ SU(3) representation (with spin one) and we might expect its decay to produce decuplet pentaquarks in association with kaons, with spectacular experimental signatures. Examples of pentaquark production in Ω_b decays are

$$\Omega_b^-(6049) \rightarrow \phi (J/\Psi \Omega^-(1672)) \quad (19)$$

$$\Omega_b^-(6049) \rightarrow K (J/\Psi \Xi(1387)) \quad (20)$$

which would correspond respectively to the formation of the following pentaquarks:

$$\mathbb{P}_{\mathbf{10}}^-(\bar{c} [cs]_{s=0,1} [ss]_{s=1}) \quad (21)$$

$$\mathbb{P}_{\mathbf{10}}(\bar{c} [cq]_{s=0,1} [ss]_{s=1}) \quad (22)$$

$q = u, d$. These transitions are obtained assuming that the initial $[ss]$ diquark in Ω_b^- is left unbroken by the decay process. More transitions can be found relaxing this condition.

5. Conclusions

The new pentaquarks, with the parity/mass pattern observed by the LHCb Collaboration, are an evident confirmation that diquarks work as an organizing principle for a new class of hadrons we are observing since the discovery of $X(3872)$, back in 2003. In this note we have highlighted the essential features predicted by the antiquark–diquark–diquark scheme of the pentaquark, which matches the experimental evidence so far obtained.

More such exotic baryons are expected and needed to make reliable hypotheses on the way the interactions in the system are shaping the spectra. Crossing the information on pentaquarks and tetraquarks will likely be the way towards a definitive assessment of exotic hadron spectroscopy.

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² We denote strangeness by S , not to be confused with the diquark spin s .