b DECAYS: A FACTORY FOR HIDDEN CHARM MULTIQURK STATES

Franco Buccella

INFN, Sezione di Napoli, via Cintia, 80126 Napoli, Italy

E-mail: franco.buccella@na.infn.it

ABSTRACT: We assume that the two hidden charm pentaquark discovered at LHCb are built by the three light quarks and the c\bar{c} pair, both colour octets, in relative P-wave for the \( \frac{5}{2}^+ \) state and by the eigenvectors of the chromomagnetic interaction for the five constituents in S-wave for the four \( \frac{3}{2}^- \) state with masses 4360, 4410, 4490 and 4560 MeV. The ”open channel” \( p J/\psi \) has large components along the two first states and so appear as the 4380 resonance and the \( \Lambda_c \bar{D}^0 \) and \( \Sigma_c \bar{D}^* \) are ”open channels” for the lower and higher resonances, respectively. The expectation for their strange isoscalar partners is to have a mass larger by an amount of the order or smaller than the \( M_{\Lambda} - M_N \) mass difference. We account for the small width of the \( \frac{5}{2}^+ \), since its decay needs the exchange of a gluon and stress that the decays of particles with ”beauty” provide the best experimental framework for the discovery of hidden charm multiquarks. The relevance of the production mechanics shows the reason why only some of the states with non minimal number of constituents have been found.

PACS: 21.10-k, 21.10.Pc, 03.65.Pm
1 Introduction

The discovery of two pentaquarks with hidden charm in the decay [1]:

\[ \Lambda_b \rightarrow p + J/\psi + K^- \]  

(1.1)

confirms the attitude of particles with beauty to give rise to multiquark states with hidden charm previously shown by the discovery of the \((3872, 1^+)\) resonance decaying into \(J/\psi + \rho^0\) (or \(\omega\)) produced together with a kaon in the decay of \(B_q\)'s [2]. The study of states with non-minimal number of constituents started about forty years ago as well as for 2\(q\) 2\(\bar{q}\) states [3] [4] as for 6\(q\) states [5] [6] and, last but not least, for 4\(q\) \(\bar{q}\) states [7]. Their existence has received positive evidence by the analysis, which has confirmed the existence of the \(\Theta^+, Y = 2\) baryon resonance [8] and by the large cross-section at high momentum transfer of the \((3872, 1^+)\) resonance [9], which shows that it is a compact object [10] and not a molecule, which should behave as the deuteron, which is very rarely produced at high momenta [11] (I thank Prof. Antonello Polosa to bring this fact to my attention). This seems to confirm the 2\(q\) 2\(\bar{q}\) configuration for the \(X(3872)\), as explicated in [12] (see also [13]). The discovery of the two hidden charm pentaquarks gave, if necessary, a new encouragement to deepen the theoretical study of these particles. Here we assume that their spectrum may be described in terms of the chromomagnetic interaction (CMI), which has been successful to describe the mass differences of the states of the 56 of \(SU(6)\) flavor spin (the octet \(\frac{1}{2}^+\) and the decuplet \(\frac{3}{2}^+\)) [14]. Let us begin by the mechanism of their formation in the Cabibbo allowed process for the decaying \(\Lambda_b\) with amplitude proportional to \(V_{cb}^*V_{cs}\):
To give rise to the seven constituents a gluon should be emitted and converted into a $u\bar{u}$ pair. To produce the final $K^-$ the $\bar{u}$ should combine with the strange quark produced in the decay, while the $u$ may form with the spectator scalar and isoscalar diquark in the $\Lambda_b$ by color conservation an octet of color and flavor with spin parity $\frac{1}{2}^+$, which may combine with the pair $c\bar{c}$, a color octet with spin one, produced in the decay to form the pentaquarks. If the five constituents join in relative S-wave, they may give rise to the $\frac{3}{2}^-$ hidden charm pentaquark, while if the two octets are in a P-wave they may give rise to the $\frac{5}{2}^+$. In the first case, when they join, they give rise to a combination of eigenstates of the QCD hamiltonian. In both cases isospin conservation requires that the three light quarks have $I = \frac{1}{2}$. Therefore Pauli principle demands that, if they are in S-wave with a symmetric wave function, they transform as the 70 representation of $SU(6)_{cs}$ (for three objects a mixed symmetry may give rise to an antisymmetric one only by multiplying it by another mixed symmetry, since by multiplying it for a totally symmetric or antisymmetric one gets a mixed symmetry [15] [16] [17]), while the $c\bar{c}$ pair transforms as the $35 + 1$ representation of $SU(6)_{cs}$. The mechanism of the decay of the $(\frac{5}{2})^+$ pentaquark is similar to the one, which may describe the decay of the $1^+$ tetraquark at 3872 into $J/\psi + \rho^0$ (or $\omega$): a gluon exchange, which turns the two color octets into singlets. Instead their formation in the decay of $B_q$ and $\Lambda_b$ is different. In fact in the first case the strange quark produced in the $b$ decay forms a kaon together with the spectator antiquark, while the $q\bar{q}$ pair produced by the gluon forms together with the $c\bar{c}$ the $1^+(3872)$ tetraquark. The analogous process for the $\Lambda_b$ decay, with the strange quark forming with the spectator diquark a $\Lambda$ would give rise to the decay $\Lambda_b \rightarrow \Lambda + 1^+(3872)$ which might be looked for in final states $p + \pi^- (\Lambda)$, $\mu^+\mu^- (J/\psi)$ and $\pi^+\pi^- (\rho^0)$. Högaasen and Sorba [15] studied all the possibilities with three constituents in P-wave with respect to the other two and came to the conclusion that the most interesting case is with two color octets of the three light quarks and the $c\bar{c}$ pair with the caveat that each octet might be turned into an ordinary hadron by absorbing a gluon before combining to form the hidden charm pentaquark. One should keep however into account the fact that in the decay $\Lambda_b \rightarrow p + J/\psi + K^-$ a gluon should be emitted and turned into a $u\bar{u}$ pair to give rise to seven final constituents and therefore the presence of another gluon requires a higher order in QCD. As we shall stress in the following the "beautiful" particles due to their relative long lifetime decay at a distance from the interaction point sufficient to avoid the presence of the gluons emitted there. In the next section we shall show the role of the chromomagnetic interaction (the fine structure term) to describe the spectrum of the ordinary hadrons and of the two lowest scalar nonets and the mass of the doubly charmed baryon recently discovered at LHCb [18]. In the third section we will compute the masses of the two hidden charm pentaquarks. Our description will account for their different widths. In the fourth section we shall give a reason for which only some of the multiquark states have been detected. Finally we shall give our conclusion. In the Appendix we write some CG of $SU(6)$ and some identities, which are useful to compute the chromomagnetic contributions.
The spectrum of the lower negative and positive parity mesons described by the chromomagnetic interaction.

After the proposal of QCD as the theory of strong interactions [19], De Rujula, Georgi and Glashow [14] realized that the fine structure (the chromomagnetic interaction) accounts for the mass differences between $\Delta$ and the nucleon and between $\Sigma$ and $\Lambda$. In the same framework there is the successful prediction:

$$M(\Xi^+) - M(\Xi) = M(Y^+) - M(\Sigma)$$ (2.1)

which was previously obtained by assuming the same coefficients for the terms transforming as an octet for the decimet and the octet baryons. By applying the same approach to the charmed baryons $\Sigma_c$ and $\Lambda_c$, they predict a mass difference high enough to allow the strong decay $\Sigma_c^+ \rightarrow \Lambda_c + \pi^+$ in agreement with the discovery of both particles in a neutrino experiment [20] (I am grateful to Professor Alvaro De Rujula to bring [20] to my attention). Indeed the masses of these two particles are reproduced with a girochromo-magnetic factor $k_c = 0.24\ k_u$ and with an effective mass for the charmed quark 1715 MeV. The $\Sigma_b$ and $\Lambda_b$ particles have a mass difference even larger, as expected. The mass of 3621.40 MeV of the $\Xi^{++}$ recently found by LHCb [18] implies an effective mass of the constituent charmed quarks of 1665 MeV smaller than the one found for the charmed mesons and $\Lambda_c$.

As long as for mesons ($\pi$, $K$, $\rho$, $K^*$), one obtains their masses with a larger effective CMI and smaller effective mass for the light and the strange quarks. Both these properties can be understood by the more intense chromo-electric attraction between a quark and an antiquark, which form a color singlet with respect to two quarks, which combine in a $\bar{3}$ of SU(3) color. Indeed the stronger attraction implies a smaller constituent mass and a larger contact interaction. In fact for the charmed mesons $D$ and $D^*$ a slightly smaller mass, 1615 MeV, and larger $k_c = 0.26\ k_u$ are needed with respect to the charmed baryons.

Also the values found for the $c\bar{c}$ states, 1535 MeV for the mass of the charmed quark and $k^2 = 0.186$ for the square of the giro chromomagnetic factor can be understood as a consequence of the smaller distance between the constituents. For the two nonets of scalar tetraquarks, where the states built with the light constituents are the $f^0(600)$ and $f^0(1370)$, their masses are reproduced with an effective chromomagnetic interaction as for the baryons and with a larger constituent mass. Interestingly enough one explains why the lowest one, which decays into two pions, has a very large width, while the other one decays mainly into four pions [21]. In fact the SU(6) color spin Casimir, which gives the most important contribution to the masses, implies that the lighter state is almost a SU(6) color spin singlet with an "open channel" [22] into two pions, which are also color singlets, while the heavier one transforms mainly as a 405 and therefore has an open channel into a pair of $\rho$ mesons, which transform as a 35 of SU(6) color spin [23] [13]. We may be confident that also the pentaquark states are eigenvectors of the chromomagnetic interaction. A general analysis of the spectrum of negative and positive pentaquarks built with the three lightest quarks can be found in [24] and the study of $3q\ 3\bar{q}$ exaquarks in [25].
3 Formation, masses and decays of the hidden charm pentaquarks

In the Cabibbo allowed process for the decaying $\Lambda_b$ described in (2) the produced $c$, if it does not recombine with the spectator diquark $ud$ to give a $\Lambda_c$, may form a color octet with spin 1 with the $\bar{c}$. If a gluon is produced and which gives rise to a color octet $u\bar{u}$ pair, the $\bar{u}$ may combine with the $s$ produced in the decay to form a negative kaon and the $u$ with the spectator diquark in the $\Lambda_b$ may form a color octet with spin $\frac{1}{2}$ and the same flavor of the proton. The two color octets may give rise to one or the other of the two resonances, depending on their relative orbital momentum, the one with negative parity for the S-wave, the one with positive parity for the P-wave. We assume that the mass $= 4450 \text{ MeV}$ of the $\left(\frac{5}{2}\right)^+$ pentaquark is given by the sum of the constituent masses and of the contributions of the chromomagnetic interaction (CMI), which for the usual baryons reproduces the $M_\Delta - M_N$ and the $M_\Sigma - M_\Lambda$ mass differences [14] and for the charmed mesons $M_{J/\psi} - M_{\eta_c}$, of the rotational energy and of the spin orbit $\vec{L} \times \vec{S}$ terms. Within the semplifying assumption that the contribution of the chromoelectric interaction of four quarks and a $\bar{q}q$ does not depend on the way they form a color singlet, we can relate the mass of the two octets to two combinations of the mass of the $\Delta$ and the $N$ for the three light quarks and of $J/\psi$ and $\eta_c$ for the $c\bar{c}$ pair.

Starting by the formulas:

$$- \frac{m_\Delta - m_N}{4} [C(3q)6 - \frac{1}{2}C(3q)3 - \frac{1}{3}C(3q)2 - 6]$$

(3.1)

($C_n$ are the quadratic Casimir of $SU(6)_{cs}$, $SU(3)_c$ and $SU(2)_s$, respectively) for the three quarks and:

$$\frac{3}{16}(M_{J/\psi} - M_{\eta_c})[C(c\bar{c})6 - \frac{1}{2}C(c\bar{c})3 - \frac{1}{3}C(c\bar{c})2 - 4]$$

(3.2)

for the $c\bar{c}$ pair.

By adding the contribution of the constituent masses:

$$\frac{M_N + M_\Delta}{2} + \frac{3M_{J/\psi} + M_{\eta_c}}{4} = (1085.5 + 3068) \text{MeV} = 4153.5 \text{MeV}$$

(3.3)

the sum of the masses of the two octets, which build the $\left(\frac{5}{2}\right)^+$ is given by:

$$\frac{3M_\Delta + 5M_N}{8} + \frac{23M_{J/\psi} + 9M_{\eta_c}}{32} = 4127 \text{MeV}$$

(3.4)

The spin-orbit terms, which are both expected to be positive, and the rotational energy may give the remaining contribution. The narrow width of the 4450 MeV, $\frac{5}{2}^+$ should be explained by the fact that the decay into $p + J/\psi$ needs the exchange of one gluon as it was the case for the decay of the $1^-$ (3872) into $J/\psi + \rho^0$ (or $\omega$), if one identifies it as the state built with the light $(q\bar{q})$ and the charmed $(c\bar{c})$ pairs transforming as the $(8, 3)$ representation of $SU(3) \times SU(2)$ color spin [12]. One has with all the constituents in S-wave four states with $S = \frac{3}{2}$, which can be obtained by the products $\frac{3}{2} \times 1$, $\frac{3}{2} \times 0$ and $\frac{1}{2} \times 1$. Let us remember that the 70 contains both $\frac{3}{2}$ and $\frac{1}{2}$ spin color octets and a spin $\frac{1}{2}$ singlet, while the 35 contains both 1 and 0 spin color octets and a spin 1 color singlet.
we have the following possibilities for the color-spin transformation properties of the three light quarks and the $c\bar{c}$ pair:

$$(8, \frac{3}{2}) \times (8, 1) \text{ combined into a } (1, \frac{3}{2})$$  \hspace{1cm} (3.5)

$$(8, \frac{3}{2}) \times (8, 0) \text{ combined into a } (1, \frac{3}{2})$$  \hspace{1cm} (3.6)

$$(8, \frac{1}{2}) \times (8, 1) \text{ combined into a } (1, \frac{3}{2})$$  \hspace{1cm} (3.7)

$$(1, \frac{1}{2}) \times (1, 1) \text{ combined into a } (1, \frac{3}{2})$$  \hspace{1cm} (3.8)

One has also to consider the chromomagnetic interaction between the charmed and the light quarks and their different chromomagnetic factors $^{[26]} [16]$. The total contribution of CMI, $M$, is given by:

$$M = M(70) + M(70 \times 6) + M(70 \times \bar{6}) + M(6 \times \bar{6})$$  \hspace{1cm} (3.9)

The sum of the contributions of the first and the fourth terms to the states defined in eqs.(8...11) is given by:

$$\frac{m_{\Delta} - m_N}{8} - \frac{m_{J/\psi} - m_{\eta_c}}{32}$$  \hspace{1cm} (3.10)

for (8)

$$\frac{m_{\Delta} - m_N}{8} + \frac{3(m_{J/\psi} - m_{\eta_c})}{32}$$  \hspace{1cm} (3.11)

for (9)

$$- \frac{M_{\Delta} - M_N}{4} - \frac{M_{J/\psi} - M_{\eta_c}}{32}$$  \hspace{1cm} (3.12)

for (10)

while for the "open channel" (11) is:

$$\frac{M_N - M_{\Delta}}{2} + \frac{M_{J/\psi} - M_{\eta_c}}{4}$$  \hspace{1cm} (3.13)

The second and the third term, related to the chromomagnetic interaction of the light quarks with $c$ and $\bar{c}$, are proportional to $k_1 = 0.24$ and $k_2 = 0.26$, respectively. To evaluate them one should consider the tensor products:

$$70 \times 6 = 210 + 105 + 105'$$  \hspace{1cm} (3.14)

$$70 \times \bar{6} = 384 + 21 + 15$$  \hspace{1cm} (3.15)

and the fact that the $(3, 5)$ of $SU(6)^{cs}$ is contained in the $105'$, while the three $(3, 3)$ in the three representation of the first product, and that one of the $(\bar{3}, 3)$ is contained in the
15 and the $(3, 5)$ and the other two $(3, 3)$'s in the 384 for the second product. In conclusion the terms proportional to:

$$(M_\Delta - M_N)$$

and

$$(M_\rho - M_\pi) = \frac{1}{k^2}(M_{J/\psi} - M_{\eta_c})$$

are the matrices:

$$\begin{array}{cccc}
1+3k_1 & 0 & 0 & 0 \\
0 & 1-3k_1 & \frac{k_1}{3} & \frac{k_1}{6} \\
0 & \frac{k_1}{3} & 1 & \frac{k_1}{6} \\
0 & \frac{k_1}{6} & \frac{k_1}{6} & \frac{k_1-1}{2}
\end{array}$$

Table 1.

| $3k_2(-9+k_2)$ | $\sqrt{15}(3+k_2)$ | $\sqrt{15}k_2$ | $-\sqrt{15}k_2$ |
|----------------|-----------------|--------------|-----------------|
| $\frac{64}{16}$ | $\frac{64}{16}$ | $\frac{8}{16}$ | $\frac{8}{16}$ |
| $-\sqrt{15}(3+k_2)$ | $-15+k_2)k_2$ | $\sqrt{15}k_2$ | $-\sqrt{15}k_2$ |
| $-\sqrt{15}k_2$ | $-\frac{k_2}{8}$ | $-(3-k_2)k_2$ | $\frac{k_2}{8}$ |
| $-\sqrt{15}k_2$ | $-\frac{k_2}{16}$ | $-\frac{k_2}{32}$ | $\frac{(k_2)^2}{32}$ |

Table 2.

respectively.

We get the following M matrix in MeV for the total contribution of the chromomagnetic interaction in the base of the states:

$$|1\rangle = |70 \times 6, (8, 4) \times (3, 2) \rightarrow (3, 5)\rangle$$

$$|2\rangle = |70 \times 6, (8, 4) \times (3, 2) \rightarrow (3, 3)\rangle$$

$$|3\rangle = |70 \times 6, (8, 2) \times (3, 2) \rightarrow (3, 3)\rangle$$

$$|4\rangle = |70 \times 6, (1, 2) \times (3, 2) \rightarrow (3, 3)\rangle$$

$$\begin{array}{cccc}
10.5 & -33 & -71.5 & -35.05 \\
-33 & 28.75 & 5.3 & 2.65 \\
-71.5 & 5.3 & 53.2 & 6.5 \\
-35.05 & 2.65 & 6.5 & 86.2
\end{array}$$

Table 3.

which has the eigenvalues: - 120, - 71, 11 and 80 in correspondence to the eigenvectors:

$$(.057, .08, .59, .624)$$

$$(.225, .063,.604, -.762)$$

$$(.39, .847, -.35, -.094)$$
The lowest charmed mesons, respectively: 

The relationship between the \((8 \times 8)\) masses of the light quarks from the lowest baryons and of \(c\) and \(\bar{c}\) from the \(\Lambda_c\) and from the lowest charmed mesons, respectively:

\[
\frac{M_{\Lambda} - M_N}{2} + M_{\Lambda_c} + \frac{3M_{D^*} + M_D}{4} = 4480\text{MeV} \tag{3.17}
\]

which implies for the two lightest \(\frac{3}{2}^-\) states a mass of 4360 and 4410 MeV. Indeed, by taking the masses of charmed constituents from charmonium would lead to smaller constituent masses, but the presence of the three light quarks favors to consider charmed baryon and mesons and the tendency of larger constituent masses with the increasing number of constituents in relative S-wave may give rise to a global constituent mass so well reproducing the experimental value. Indeed the \(Q^2\) dependence of the strong coupling constant, decreasing with the scale, might be an explanation for the different values of the constituent masses for the ordinary mesons and baryons as well as for the different value at the scale of the negative parity states built with all the constituents \(3q, c\) and \(\bar{c}\) in S-wave. Indeed for the lowest scalar tetraquarks built with light constituents the effective masses of the constituents is about 400 MeV, larger than in the case of ordinary baryons.

The value found has the important consequence to predict two higher \(\frac{3}{2}^-\) states at 4490 and 4560 MeV. By considering \(qqc\bar{c}\) combinations the "open channels" \(\Lambda_cD^{*0}\) and the \(I = \frac{1}{2}\) combination \(\frac{1}{\sqrt{3}}(\sqrt{2}\Sigma^+_c + D^* - \Sigma^+_c D^{*0})\) have different components along the CMI eigenvectors. While \(\Lambda_c D^{*0}\) with total spin \(\frac{1}{2}\) for the light quarks is a combination of the two last vectors and therefore has substantial components along the two lower mass eigenstates, \(\frac{1}{\sqrt{3}}(\sqrt{2}\Sigma^+_c + D^* - \Sigma^+_c D^{*0})\) has components mainly along the two states with spin \(S(uud) = \frac{3}{2}\) for the light quarks, as it can be seen from the identity for the states with \(S = \frac{3}{2}\):

\[
|S(uu) = 1, S(uuc) = \frac{1}{2}, S(\bar{c}c) = 1 > = \frac{1}{3}\sqrt{5}|S(uud) = \frac{3}{2}, |S(\bar{c}c) = 1 > - \sqrt{3}|S(uud) = \frac{3}{2}S(\bar{c}c) = 0 > + |S(uud) = \frac{1}{2}, S(\bar{c}c) = 1 > \tag{3.18}
\]

The relationship between the \((8 \times 8)\) and \(1 \times 1\) for \(uud\) and \(\bar{c}c\) and \(uuc\) \(d\bar{c}\) is supplied by the well known \(SU(3)\) identities:

\[
\delta^2_\alpha \delta^2_\gamma = \frac{1}{3} \delta^2_\alpha \delta^2_\gamma + \frac{1}{2} (\lambda_\alpha)_\alpha^\gamma (\lambda_\gamma)_\gamma^\alpha \tag{3.19}
\]

\[
(\lambda_\alpha)_\alpha^\gamma (\lambda_\gamma)_\gamma^\alpha = \frac{16}{3} \delta^2_\alpha \delta^2_\gamma - \frac{1}{3} (\lambda_\alpha)_\alpha^\gamma (\lambda_\gamma)_\gamma^\alpha \tag{3.20}
\]

The fact that the chromomagnetic interaction for the light quarks (the ones with the higher girochromomagnetic factor) gives a positive contribution for the state \(\Sigma_c D^*\) and negative for \(\Lambda_c D^{*0}\) (in analogy with the large difference \(M_{\Sigma_c} - M_{\Lambda_c}\) \([14] [20]\)) leads us to guess that the \(\Sigma_c D^*\) and \(\Lambda_c D^{*0}\) "open channels have large components along the 4560 and 4360 MeV
resonances, respectively. However, according to the formation mechanism starting from the third state \((8, \frac{1}{2}) \times (8, 1)\), which has a negligible component along the higher eigenstate, the \(\Sigma_c \bar{D}^*\) decay may be more easily seen for the 4490 resonance. For the decay of the \(\Sigma^{++}_c\) we may have the same sequence:

\[
\begin{align*}
\Sigma^{++}_c & \to \Lambda_c + \pi^+, \\
\Lambda_c & \to p + K^- \pi^+ 
\end{align*}
\]

which lead to the discovery of \(\Sigma^{++}_c\) in a neutrino experiment [20].

If it is the strange quark produced in the weak decay to form a strange color octet together with the scalar and isoscalar spectator in \(\Lambda_b\), similar to the description of the formation of the 3872 \(1^+\) in B decays [27], we can give a qualitative description of the spectrum of the strange isoscalar pentaquark with hidden charm. As long as for the \(\frac{5}{2}^+\) the CMI interaction for the color octet \(\frac{1}{2}^+\) is the same as for the \(udu\) case and we should simply add the \(M_\Lambda - M_N\) mass difference. We expect however smaller positive contributions from the rotational energy and the spin-orbit terms and therefore predict the upper limit 4625 MeV. For the \(\frac{3}{2}^-\) states the contribution of the light quarks, the ones with the higher girochromomagnetic factor, to the CMI is the same and so we expect approximately for the four \((\frac{3}{2})^-\) states the following values for the masses: 4535, 4585, 4665 and 4735 MeV, respectively.

In general it is not easy to produce hadrons with non minimal number of constituents, since the \(q\) and \(\bar{q}\) produced by the gluons tend fastly to combine into color singlets and the easiest way is to form ordinary hadrons. In Cabibbo allowed B decays the creation of a \(c\bar{c}\) color octet pair, which exerts an actraction on another octet built with a \(q\bar{q}\) pair or three light quarks, can give rise to hadron states with hidden charm.

In conclusion the interpretation of the two pentaquark resonances with hidden charm discovered at \textit{LHCb} [1] as built with a \(c\bar{c}\) and three light quark color octets in P-wave for the \((\frac{3}{2})^+\) and with the five constituents in S-wave for the \((\frac{1}{2})^-\) accounts for their different widths. An important consequence of this description is the prediction of two \((\frac{3}{2})^-\) resonance at a mass of 4360 and 4560 MeV, with large components along the "open channels" \(\Lambda_c \bar{D}^{*0}\) and \(\Sigma_c \bar{D}^*\) final states, respectively. As we shall stress in the following section the "beautiful" particle due to their relative long lifetime decay at a distance from the interaction point sufficient to avoid the presence of the gluons emitted there, which give rise to \(q\bar{q}\) pairs transforming as color octets with the \(q\)’s and the \(\bar{q}\)’s, which build with the other constituents ordinary hadrons.

### 4 Formation of multiquark states

The fact that the 3872, \(1^+\), which is a compact object, since it is produced also at high \(p_T\) at difference from the deuton is seen only for its neutral component shows the relevance of the formation of multiquark states. In fact the mechanism described is operative only for the neutral component [27], which is indeed the only component discovered.

In fact as long as for the states predicted by Jaffe [22] strong evidence concerns only the two scalar nonets, the multiplet consisting of \(f^0(600), k(770)\) and \(f^0\) and \(A^0\), degenerate as expected, at 980 MeV and the one, where \(f^0(1370)\) is the one consisting of light constituents.
This lead the Roma group [28] to consider only the diquarks transforming as \((\bar{3}, S = 0, \bar{3})\) with respect to \(SU(3)_c \times SU(2)_s \times SU(3)_f\) and their antiparticles, which may give rise only to one scalar nonet. To account for the heavier one they advocate an istanton [29]. As we have shown in the second section the masses and decays of the two states built with the light constituents are well described by deducing their spectrum with the same approach followed in [14] for ordinary hadrons. In fact, when the \(\bar{3}, S = 0 \text{ and } 3, S = 0\) join, they give rise to a superposition of eigenstates of the CMI, with ”open channel” [22] two pions or two \(\rho\)'s, respectively. To build the 3872 \(1^+\) the Roma group considered also diquarks transforming as a \((\bar{3}, 3)\) under \(SU(3)_c \times SU(2)_s\) [30]. For these diquarks the chromoelectric force is attractive, while the chromomagnetic is repulsive, which makes their formation less probable. Moreover, as well as the diquark \((\bar{3}, 1)\), they may combine with a quark to form a baryon. The \((\bar{3}, 3)\) may also give rise to a flavor decimet and therefore a lower limit to the ratio of the abundances of \((\bar{3}, 3)\) and \(\bar{3}, 1\) may be given by the ratio of the non-diffractive productio of \(\Delta\) and \(N\). Diquarks are considered to build tetraquarks [31] as well as for pentaquarks [32] with a description different from the one presented here. The mechanism proposed here for the formation of the 3872, \(1^+\), which accounts for the fact that only its neutral component has been found, is at our advice better motivated. The tendency of the diquark \((\bar{3}, 3)\) to form a baryon with the quark rather than combine with a \((3, 1)\) diquark to build a spin 1 state or with a \((\bar{3}, 3)\) diquark to give rise to spin and (or) isospin 2 states explains why the large class of states predicted by Jaffe has not yet been found. At our advice the approach based on the extension to the multiquark states of the one introduced in [14] for the ordinary baryons, which may be successfully extended to ordinary mesons, to find their spectrum is valid, but a production mechanism is needed to prevent that the formation of those states is not overwhelmed by the recombination of the \(q\) and \(\bar{q}\) produced by the gluons into ordinary hadrons. To this extent the decays of the particles with beauty produced at Belle and BaBar, but also at \(LHCb\) is a favourable situation, since the ”beautiful” particles decay in absence of associated production. This is evident for the \(e^+e^-\) rings, but it happens also for the particles produced at \(LHCb\), since the long lifetime of the \(b\) quark, which allows the hadrons with beauty to leave the interaction point before decaying, implies that the products of their decays are not surrounded by the \(q\bar{q}\) pairs produced in the interaction. As long as for the formation of the \(\Xi^{*+}_{cc}\) previously mentioned [18], it is probably due to the union of a \(cc\) scalar diquark with a \(u\). While its decay into \(\Lambda_c + K^+ + \pi^+\pi^+\) requires that the allowed Cabibbo decay is accompanied by the creation of both a \(u\bar{u}\) and a \(d\bar{d}\) pairs, the \(\Lambda_c \rightarrow P + K^- + \pi^+\) implies the formation of a \(u\bar{u}\) pair.

5 Conclusions.

The approach based on the chromomagnetic interaction to find the spectrum of the multiquark states, applied successfully for the 3872, \(1^+\) [12] and to the lowest scalar nonets [13], is confirmed by the discovery of the two hidden charm pentaquarks at \(LHCb\), since it accounts for the different widths of the \(\frac{3}{2}^-\) and \(\frac{5}{2}^+\) resonances. A confirm of the description proposed here should be the detection of \(\Sigma_c, D^*\) and \(\Lambda_c, \bar{D}^*\) final states and of isoscalar strange hidden charm pentaquarks with a mass around or minor than the sum of
the mass of their non strange partners and the mass difference $M_A - M_N$. The property of the beautiful particles of travelling away from the interaction point, as a consequence of their lifetime, prevents the formation of hidden charm multiquarks after the Cabibbo favored decay with the production of a pair $c\bar{c}$ from being overwhelmed by the production of ordinary hadrons, which is the reason why many multiquark states have not been found.

6 Acknowledgement.

I am very grateful to Prof. Mario Abud for his explanation of the non detection of the charged partners of the 3872, which inspired the considerations on the relevance of the formation mechanism of multiquark states.

References

[1] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 115 072001 2015
[2] S. K. Choi et al. (Belle Collaboration), Phys. Rev. Lett. 91 252001 2003
D. Acosta et al. (CDF Collaboration), Phys. Rev. Lett. 93 072001 2004
V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 93 162002 2004
B. Aubert et al. (BaBar Collaboration), Phys. Rev. D71 071103 2005
R. A. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 110 222001 2013
[3] R. L. Jaffe, Phys. Rev. D15 267 and 281 1977
[4] H. M. Chan and H. Høgaasen Phys. Lett. B76 634 1978
[5] R. L. Jaffe, Phys. Rev. Lett. bfl 38 195 and 617 1977
[6] V. A. Matveev and P. Sorba, Lett.Nuovo Cimento 20 121 1977 and Nuovo Cimento A45 257 1978
[7] H. Høgaasen and P. Sorba, Fizika B14 2,245 2005
[8] Ya. I. Azimov, J. Phys. G37 023001 2010 and Proceedings of the International Workshop "Hadron Structure and QCD" 158 edited by V. T. Kim and L. V. Lipatov
[9] S. Chatchyan et al. (CMS Collaboration), J. High Energy Phys. D4 154 2013
[10] A. Esposito, A.L. Guerrieri, L. Maiani, F. Piccinini, A. Pilloni, A. D. Polosa and V. Riquer, Phys. Rev. D92 034028 2015
[11] J. Adam et al. (ALICE Collaboration), arXiv: 1506 08453 and 08951
B. Abelev et al. (ALICE Collaboration), Phys. Rev. C88 044909 2013
[12] H. Høgaasen, J. M. Richard and P. Sorba, Phys. Rev. D73 054013 2006
[13] F. Buccella, H. Høgaasen, J. M. Richard and P. Sorba Eur. Phys. J. C49 743 2007
[14] A. De Rújula, H. Georgi and S.L. Glashow, Phys. Rev. D12 147 1975.
[15] H. Høgaasen and P. Sorba, Nucl. Phys. B145 119 1978
[16] M. de Combrughes, H. Høgaasen and P. Sorba, Nucl. Phys. B156 1979 347
[17] F. Buccella and P. Sorba, Mod. Phys. Lett. A19 1547 2004.
[18] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 119 112001 2017
the three light quarks and of $\bar{c}$, |$SU(3)$.

Appendix

The evaluation of the contributions proportional to $k_1$, $k_2$ and $k^2$ require the knowledge of the following CG of $SU(6)$ color spin:

$$|105', 3, S = 2> = |70 \times 6, 8 \times 3, \frac{3}{2} \times \frac{1}{2}>$$

$$|105', 3, S = 1> = \frac{1}{\sqrt{6}} \left[ |70 \times 6, 8 \times 3, \frac{3}{2} \times \frac{1}{2}> + 2 |70 \times 6, 1 \times 3, \frac{1}{2} \times \frac{1}{2}> + |70 \times 6, 1 \times 3, \frac{1}{2} \times \frac{1}{2}> \right]$$

$$|105, 3, S = 1> = \frac{1}{\sqrt{3}} \left[ |70 \times 6, 8 \times 3, \frac{3}{2} \times \frac{1}{2}> + 2 |70 \times 6, 1 \times 3, \frac{1}{2} \times \frac{1}{2}> - |70 \times 6, 1 \times 3, \frac{1}{2} \times \frac{1}{2}> \right]$$

$$|210, 3, S = 1> = \frac{1}{\sqrt{2}} \left[ |70 \times 6, 8 \times 3, \frac{3}{2} \times \frac{1}{2}> - |70 \times 6, 8 \times 3, \frac{1}{2} \times \frac{1}{2}> \right]$$

$$|384, 3, \bar{S} = 2> = |70 \bar{6}, 8 \bar{3}, \frac{3}{2} \times \frac{1}{2}>$$

$$|384_1, 3, \bar{S} = 1> = \frac{1}{\sqrt{105}} \left[ 5 |70 \bar{6}, 8 \bar{3}, \frac{3}{2} \times \frac{1}{2}> - 8 |70 \bar{6}, 8 \bar{3}, \frac{1}{2} \times \frac{1}{2}> - 4 |70 \bar{6}, 1 \times 3, \frac{1}{2} \times \frac{1}{2}> \right]$$

$$|384_2, 3, \bar{S} = 1> = \frac{1}{\sqrt{5}} \left[ |70 \bar{6}, 8 \bar{3}, \frac{1}{2} \times \frac{1}{2}> - 2 |70 \bar{6}, 8 \bar{3}, \frac{1}{2} \times \frac{1}{2}> \right]$$

$$|15, 3, \bar{S} = 1> = \frac{1}{\sqrt{21}} \left[ 4 |70 \bar{6}, 8 \bar{3}, \frac{3}{2} \times \frac{1}{2}> + 2 |70 \bar{6}, 8 \bar{3}, \frac{1}{2} \times \frac{1}{2}> + 1 |70 \bar{6}, 1 \times 3, \frac{1}{2} \times \frac{1}{2}> \right]$$

where $S$ is the total spin of the three light quarks and of $c$ and $\bar{S}$ is the total spin of the three light quarks and of $\bar{c}$. If the spin of the light quarks and the total spin are both
The following identities follow:

\[
|S = 2> = -\frac{1}{4}[|\bar{S} = 2> + \sqrt{15}|S = 1>] = \frac{1}{\sqrt{8}}[\sqrt{3}|S_{c\bar{c}} = 1> + \sqrt{5}|S_{c\bar{c}} = 0>]
\]

\[
|S = 1> = \frac{1}{4}[|\sqrt{15}\bar{S} = 2> - |\bar{S} = 1>] = \frac{1}{\sqrt{8}}[\sqrt{5}|S_{c\bar{c}} = 1> - \sqrt{3}|S_{c\bar{c}} = 0>]
\]  (7.1)