Compact pentaquark structures

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We investigated the possibility that the lightest pentaquark state recently reported by the LHC_b Collaboration [R. Aaij *et al.*, Phys. Rev. Lett. **115**, 072001 (2015); **117**, 082002 (2016); **117**, 082003 (2016)], $P_c^+(4380)$, could be described as a compact pentaquark state. By using very general arguments, dictated by symmetry considerations, we described the pentaquark states within a group theory approach. A complete classification of all possible states and quantum numbers, which can be useful both to the experimentalists in their search for new findings and to theoretical model builders, is given, without introducing any particular dynamical model. Some predictions are provided by means of a Gürsey-Radicati inspired mass formula. We have reproduced the mass and the quantum numbers of the lightest pentaquark state reported by LHC_b, $P_c^+(4380)$, and have predicted other pentaquark resonances which belong to the same multiplet as the lightest one. Having calculated the masses of these resonances, we suggest possible bottom baryon decay channels which involve the predicted resonances as intermediate states. Finally, we have computed the partial decay widths for all the predicted pentaquark resonances.

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I. INTRODUCTION

The LHC_b Collaboration has recently reported the observation of two exotic structures, $P_c^+(4380)$ and $P_c^+(4450)$, in Λ_b decay [1]; these have been further supported by another two articles by the same collaboration [2,3].

The $\Lambda_b^0 \to J/\Psi K^- p$ decays can proceed according to the diagram shown in Fig. 1,

$$\Lambda_b^0 \to J/\psi + \Lambda^*. \tag{1}$$

They could also have exotic contributions, which have been referred to as charmonium-pentaquark states, as indicated by the diagram shown in Fig. 2,

$$\Lambda_b^0 \to P_c^+ + K^-. \tag{2}$$

These two pentaquark states are found to have masses of $4380 \pm 8 \pm 28$ MeV and $4449.8 \pm 1.7 \pm 2.5$ MeV with corresponding widths of $205 \pm 18 \pm 86$ MeV and $39 \pm 5 \pm 19$ MeV. Moreover, according to the LHC_b Collaboration [1], the preferred J^P assignments are $3/2^-$ and $5/2^+$, respectively.

Since the LHC_b observation many explanations for the pentaquark states have been proposed. Meson-baryon molecules were suggested in [4–9], pentaquark states of diquark-diquark-antiquark nature were suggested in [10,11], and $\bar{D}$ soliton states in [12].

The heaviest resonant state is well explained by the molecular interpretation (see, for example, [4]). In the present study, we therefore focused on the lightest pentaquark structure, $P_c^+(4380)$, and adopted a multiquark approach. Having shown that the pentaquark ground multiplet is a $SU_f(3)$ octet with spin $S = \frac{3}{2}$, we studied all the charmonium pentaquark states which belong to the octet, predicted their masses, and suggested possible bottom baryon decay channels which involve the predicted resonances as intermediate states. By using an effective Lagrangian [13] for the $P_c^+ J/\Psi$ coupling, in combination with the branching ratio $\mathcal{B}(P_c^+ \to J/\Psi p)$ upper limit extracted by Wang *et al.* [14], and with our predicted masses, we computed the partial decay widths for the predicted pentaquark resonances.

II. CLASSIFICATION OF THE $qqqc\bar{c}$ MULTIPLETS AS BASED ON SYMMETRY PROPERTIES

In classifying the pentaquark multiplets we made use of symmetry principles, as far as possible, without introducing any explicit dynamical models. We used the Young

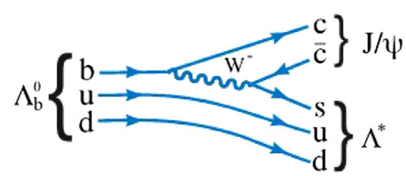

FIG. 1. Feynman diagram for $\Lambda_b^0 \to J/\psi + \Lambda^*$ decay, reported in Eq. (1) (figure taken from Ref. [1]; APS copyright).

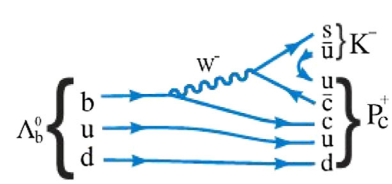

FIG. 2. Feynman diagram for $\Lambda_b^0 \to P_c^+ + K^-$ decay, reported in Eq. (2) (figure taken from Ref. [1]; APS copyright).

tableaux technique, adopting for each representation the notation $[f]_d = [f_1, \ldots, f_n]_d$, where f_i denotes the number of boxes in the ith row of the Young tableau, and d is the dimension of the representation.

In agreement with the LHC_b hypothesis [1], we think of the charmonium pentaquark wave function as $qqqc\bar{c}$ where $q = u, d, s$ is a light quark and c is the heavy charm quark.

Let us first discuss the possible configurations of qqq quarks in the $qqqc\bar{c}$ system. The $c\bar{c}$ pair can be a color octet or singlet with spin 0 or 1. The color wave function of the $qqqc\bar{c}$ system must be an $SU_c(3)$ singlet, so the remaining three light quarks are also in a color singlet, or in a color octet.

The orbital symmetry of the quark wave function depends on the quantum numbers of the pentaquark state $P_c^+(4380)$. Indeed, the parity P of the pentaquark system is

$$\mathrm{P}|qqqc\bar{c}\rangle = (-1)^{l+1}|qqqc\bar{c}\rangle, \tag{3}$$

where l is the angular momentum. In the hypothesis that the lightest pentaquark state has $J^{\mathrm{P}} = \frac{3}{2}^-$, from Eq. (3) it can be seen that the orbital angular momentum can be $l = 0$, 2, or 4.

In this paper, we hypothesize that the lightest charmonium pentaquark state reported by the LHC_b Collaboration, $P_c^+(4380)$, is a ground-state pentaquark with $l = 0$, and so each quark is in the S wave.

The three-light-quark wave function must satisfy the Pauli principle, so the spin-flavor part and the color part are conjugated: spin-flavor symmetric state if they are in a color singlet, or spin-flavor mixed symmetry state if they are in a color octet. Therefore, the allowed $SU_{sf}(6)$ spin-flavor pentaquark configurations are a 56-plet, which corresponds to the three quarks in a color singlet, and a 70-plet, which corresponds to the three light quarks in a color octet. Table I reports the analysis of the flavor and spin content of the spin-flavor 56-plet and of the 70-plet, i.e., their decomposition into the representations of $SU_f(3) \otimes SU_s(2)$. The $SU_{sf}(6)$ 56-plet contains a $SU_f(3)$ flavor octet $[21]_8$ and a decuplet $[3]_{10}$, while the 70-plet contains a $SU_f(3)$ flavor singlet $[111]_1$, two octets $[21]_8$, and a decuplet $[3]_{10}$. Therefore, the allowed $SU_f(3)$ flavor representations to which the charmonium pentaquark states can belong are

$$[111]_1, \qquad [21]_8, \qquad [3]_{10}. \tag{4}$$

In the case of three flavors (u, d, s), the hypercharge Y is defined as

$$Y = B + \mathbf{S}, \tag{5}$$

where B is the baryonic number, and $\mathbf{S}$ is the strangeness. Since the charmonium pentaquark state $P_c^+(4380)$, as reported by LHC_b, has a quark content $uudc\bar{c}$, it does not have strange quarks; thus $\mathbf{S} = C = 0$, the baryonic number is $B = 1$, and Y must be equal to 1.

TABLE I. Spin-flavor decomposition of the two allowed $SU_{sf}(6)$ spin-flavor pentaquark configurations: the 56-plet and the 70-plet.

$SU_{\mathrm{sf}}(6)$	$\supset$	$SU_{\mathrm{f}}(3)$	$\otimes$	$SU_{\mathrm{s}}(2)$
$[3]_{56}$		$[3]_{10}$	$\otimes$	$[3]_4$
		$[21]_8$	$\otimes$	$[21]_2$
$[21]_{70}$		$[3]_{10}$	$\otimes$	$[21]_2$
		$[21]_8$	$\otimes$	$[3]_4$
		$[21]_8$	$\otimes$	$[21]_2$
		$[111]_1$	$\otimes$	$[21]_2$

The singlet $[111]_1$ does not have any submultiplets with hypercharge $Y = 1$, and so it must be excluded. For this reason, the remaining possible $SU_f(3)$ multiplets for the charmonium pentaquark states are the octet and the decuplet,

$$[21]_8, \qquad [3]_{10}. \tag{6}$$

III. THE EXTENSION OF THE GÜRSEY-RADICATI MASS FORMULA

In order to determine the mass splitting between the multiplets of Eq. (6), we used a Gürsey-Radicati (GR)-inspired formula [15]. As yet, there is experimental evidence of only two charmonium pentaquark states; these are not sufficient to determine all parameters in the GR mass formula. For this reason, we used the values of the parameters determined from the three-quark spectrum (reported in Table II), assuming that the coefficients in the GR formula are the same for different quark systems. The simplest GR formula extension which distinguishes the different multiplets of $SU_f(3)$ is

$$M_{GR} = M_0 + AS(S+1) + DY + E\left[I(I+1) - \frac{1}{4}Y^2\right] + GC_2(SU(3)) + FN_C, \tag{7}$$

where M_0 is a scale parameter: this means that, for example, in baryons, each quark makes a contribution of roughly $\frac{1}{3}M_0$ to the whole mass; I and Y are the isospin and hypercharge, respectively, while $C_2(SU(3))$ is the eigenvalue of the $SU_f(3)$ Casimir operator. Finally, N_C is a counter of c quarks or $\bar{c}$ antiquarks: this term takes into account the mass difference between a c quark (or a $\bar{c}$ antiquark) and the light quarks (u, d).

The approach adopted in evaluating the coefficients A, D, E, G, F, and the scale parameter M_0 is to fit them at the same time, in order to obtain the best reproduction of the spectrum of all the ground-state charmed baryons, the ground-state hyperons, and the ground-state nonstrange baryons (here ground-state baryon means that the three constituent quarks of the baryon are in the S wave). The mass spectrum of these baryons is reported in Table II, while their quantum number assignments are reported in Table III. The fitted parameters and their corresponding uncertainties are reported in Table IV.

TABLE II. Mass spectrum of all the ground-state charmed baryons, the ground-state hyperons, and the ground-state non-strange baryons, as from Particle Data Group [16] (here ground-state baryon means that the three constituent quarks of the baryon are in the S wave).

Baryons	Experimental mass [MeV]	Experimental error [MeV]
$N(940)$	939.565413	10^{-6}
$\Lambda^0(1116)$	1115.683	0.006
$\Sigma^0(1193)$	1192.642	0.024
$\Xi^0(1315)$	1314.86	0.20
$\Delta^0(1232)$	1232	2
$\Sigma^{*0}(1385)$	1383.7	1.0
$\Xi^{*0}(1530)$	1531.80	0.32
$\Omega^-(1672)$	1672.45	0.29
$\Lambda_c^+(2286)$	2286.46	0.14
$\Sigma_c^0(2455)$	2453.75	0.14
$\Xi_c^0(2471)$	2470.85	$^{-0.40}_{+0.28}$
$\Xi_c^{\prime 0}(2576)$	2577.9	2.9
$\Omega_c^0(2695)$	2695.2	1.7
$\Omega_c^{*0}(2770)$	2765.9	2.0
$\Sigma_c^{*0}(2520)$	2518.48	0.2
$\Xi_c^{*0}(2645)$	2649.9	0.5

TABLE III. Quantum number assignment for the baryons reported in Table II; the notation is the same as that used in Eq. (7).

Baryons	$SU_f(3)$ Multiplet	$C_2(SU(3))$	S	Y	I	N_c
$N(940)$	$[21]_8$	3	$\frac{1}{2}$	1	$\frac{1}{2}$	0
$\Lambda^0(1116)$	$[21]_8$	3	$\frac{1}{2}$	0	0	0
$\Sigma^0(1193)$	$[21]_8$	3	$\frac{1}{2}$	0	1	0
$\Xi^0(1315)$	$[21]_8$	3	$\frac{1}{2}$	-1	$\frac{1}{2}$	0
$\Delta^0(1232)$	$[3]_{10}$	6	$\frac{3}{2}$	1	$\frac{3}{2}$	0
$\Sigma^{*0}(1385)$	$[3]_{10}$	6	$\frac{3}{2}$	0	1	0
$\Xi^{*0}(1530)$	$[3]_{10}$	6	$\frac{3}{2}$	-1	$\frac{3}{2}$	0
$\Omega^-(1672)$	$[3]_{10}$	6	$\frac{3}{2}$	-2	0	0
$\Lambda_c^+(2286)$	$[11]_3$	$\frac{4}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	0	1
$\Sigma_c^0(2455)$	$[2]_6$	$\frac{10}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	1	1
$\Xi_c^0(2471)$	$[11]_3$	$\frac{4}{3}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{2}$	1
$\Xi_c^{0\prime}(2576)$	$[2]_6$	$\frac{10}{3}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{2}$	1
$\Omega_c^0(2695)$	$[2]_6$	$\frac{10}{3}$	$\frac{1}{2}$	$-\frac{4}{3}$	0	1
$\Omega_c^{*0}(2770)$	$[2]_6$	$\frac{10}{3}$	$\frac{3}{2}$	$-\frac{4}{3}$	0	1
$\Sigma_c^{*0}(2520)$	$[2]_6$	$\frac{10}{3}$	$\frac{3}{2}$	$\frac{2}{3}$	1	1
$\Xi_c^{*0}(2645)$	$[2]_6$	$\frac{10}{3}$	$\frac{3}{2}$	$-\frac{1}{3}$	$\frac{1}{2}$	1

TABLE IV. Values of the parameters in the GR mass formula extension [Eq. (7)] with the corresponding uncertainties.

	M_0	A	D	E	F	G
Values [MeV]	940.0	23.0	-158.3	32.0	1354.6	52.5
Uncertainties [MeV]	1.5	1.2	1.3	1.3	18.2	1.3

TABLE V. Possible charmonium pentaquark multiplets [see Eq. (6)], with their corresponding eigenvalues of the Casimir operator $C_2(SU(3))$.

$SU_f(3)$ multiplet	$C_2(SU(3))$
$[3]_{10}$	6
$[21]_8$	3

IV. APPLICATION OF THE GR FORMULA TO THE PENTAQUARK STATES

In Eq. (6) we reported the possible $SU_f(3)$ multiplets for the charmonium pentaquark states. We hypothesize that the lightest pentaquark state reported by the LHC_b Collaboration, $P_c^+(4380)$, belongs to the lowest mass $SU_f(3)$ multiplet. According to the GR formula of Eq. (7), the mass splitting between the different $SU_f(3)$ multiplets of Eq. (6) is due to the different eigenvalues of the Casimir operator $C_2(SU(3))$; this mass splitting is proportional to the coefficient G (reported in Table IV). Since G is positive ($G = 52.5$ MeV), the lowest mass multiplet is the one with the lowest eigenvalue of the Casimir operator; thus as can be seen from Table V, the charmonium pentaquark ground state is the $[21]_8$ $SU_f(3)$ octet. For this reason, the lightest pentaquark state reported by the LHC_b Collaboration, $P_c^+(4380)$, is expected to belong to a $SU_f(3)$ octet.

In the following, we focus on the octet charmonium pentaquark states, and apply the GR mass formula (7), with the values of the parameters reported in Table IV, to each state of the octet, in order to predict the corresponding mass.

The octet pentaquark states are reported in Fig. 3, while the predicted masses, with the corresponding uncertainties, are reported in Table VI. Regarding the notation, a pentaquark state is labeled as $P^{ij}(M)$, where $i = 0, 1, 2$ is the number of strange quarks, $j = -, 0, +$ is the pentaquark's electric charge, and M is the predicted mass.

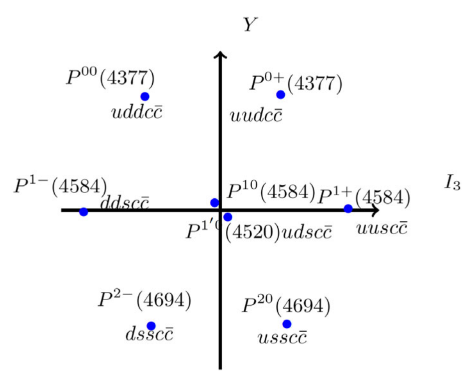

FIG. 3. Octet of the charmonium pentaquark states: each state is labeled as $P^{ij}(M)$, where $i = 0, 1, 2$ is the number of strange quarks of a given pentaquark state, $j = -, 0, +$ is the pentaquark's electric charge, and M is the predicted mass.

TABLE VI. Predicted pentaquark states with their corresponding masses. The notation is the same as that of Fig. 3.

Predicted pentaquark states	Masses [MeV]
$P^{00}(4377), P^{0+}(4377)$	4377 ± 49
$P^{1'0}(4520)$	4520 ± 47
$P^{1-}(4584), P^{10}(4584), P^{1+}(4584)$	4584 ± 50
$P^{2-}(4694), P^{20}(4694)$	4694 ± 47

We observe, in the hypothesis that the five quarks are in the S wave, the predicted state $P^{0+}(4377)$ has the same quantum numbers as the lightest resonance (charge, spin, parity) reported by the LHC_b Collaboration, $P_c(4380)$, in [1].

Its theoretical mass, predicted by means of our GR formula extension, is $M = 4377 \pm 49$ MeV.

Despite the simplicity of the approach that we have used, this result is in agreement with the mass reported by the LHC_b Collaboration, $M = 4380 \pm 8 \pm 29$ MeV.

The compact pentaquark approach predicts that the pentaquark $P^{0+}(4377)$ is a member of an isospin doublet, with hypercharge $Y = 1$.

We observe that, if the compact pentaquark description is correct, the other octet states will also be observed by the LHC_b Collaboration. By contrast, if the pentaquark is mainly a molecular state, it is not necessary that all the states of that multiplet should exist.

V. BOTTOM BARYON DECAY CHANNELS INVOLVING INTERMEDIATE PENTAQUARK STATES

In this section, we suggest possible bottom baryon decay channels which involve the predicted pentaquark structures as intermediate states. These channels will be described in detail.

The state $P^{0+}(4377)$ is a part of an isospin doublet. A possible decay channel in which we might observe its isospin partner, $P^{00}(4377)$, could be

$$\Lambda_b^0 \to P^{00} + \bar{K}^0, \qquad P^{00} \to J/\Psi + N. \tag{8}$$

The corresponding Feynman diagram is reported in Fig. 4.

With regards to the other charmonium pentaquark states of the octet, i.e., those with strangeness, we have to focus on the decays of bottom baryons endowed with strange quarks. Let us consider the following Ξ_b^- decay:

$$\Xi_b^- \to J/\psi + \Xi^-. \tag{9}$$

This decay is present in nature and was discovered by the D0 Collaboration [17]. As in the case of the exotic Λ_b^0 decay shown in Fig. (2), we can expect that an exotic decay may also occur in the case of Ξ_b^- baryon,

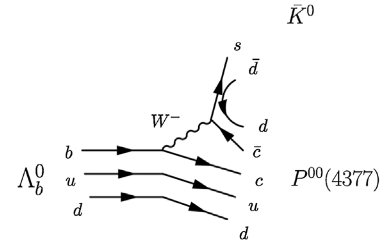

FIG. 4. Λ_b baryon decay in $P^{00}(4377)$ and $\bar{K}^{00}$, where $P^{00}(4377)$ is the neutral pentaquark state, a member of the isospin doublet with $Y = 1$.

$$\Xi_b^- \to P^{10}/P^{1'0} + K^-, \quad P^{10}/P^{1'0} \to J/\Psi + \Sigma/\Lambda. \tag{10}$$

In Eq. (10), $P^{10}(4584)$ and $P^{1'0}(4520)$ have the same quark content ($usdc\bar{c}$), and belong to the isospin triplet and to the isosinglet, respectively (see Fig. 3). Since they have the same quark content and both are neutral, they can both result from the Ξ_b^- decay.

The charmonium pentaquark state $P^{1-}(4584)$ can be observed in the following decay process:

$$\Xi_b^- \to P^{1-} + \bar{K}^0, \qquad P^{1-} \to J/\Psi + \Sigma^-. \tag{11}$$

The difference between the two suggested decay modes for the Ξ_b^- baryon [Eqs. (10) and (11)] lies in the final state: in the case of the final state shown in Eq. (10), a $u\bar{u}$ pair is created from the vacuum, whereas, in the decay of Eq. (11), the $u\bar{u}$ pair is replaced with the $d\bar{d}$ pair. The Ξ_b^- baryon is a member of an isodoublet. The decay of its isospin partner Ξ_b^0,

$$\Xi_b^0 \to P^{1+} + K^-, \qquad P^{1+} \to J/\Psi + \Sigma^+, \tag{12}$$

is probably the most important one from the experimental point of view, since all the final-state particles are charged and, therefore, easier to detect. In order to obtain a pentaquark candidate with $s = -2$ in the final state, a baryon with two strange quarks in the initial state is needed. The known decay channel of the Ω_b baryon is

$$\Omega_b^- \to J/\psi + \Omega^-. \tag{13}$$

This decay was discovered by the $D0$ detector at the Fermilab Tevatron collider [18]. Another possible Ω_b^- decay channel may be, in analogy with the exotic Λ_b decay channel shown in Fig. (2),

$$\Omega_b^- \to P^{20} + K^-, \qquad P^{20} \to J/\Psi + \Xi^0. \tag{14}$$

The state $P^{20}(4694)$ of Eq. (14) is a part of an isospin doublet (see Fig. 3). In order to observe its isospin partner $[P^{2-}(4694)]$, it may be possible to use the following decay channel:

$$\Omega_b^- \to P^{2-} + \bar{K}^0, \qquad P^{2-} \to J/\Psi + \Xi^-. \tag{15}$$

The difference between the Ω_b^- decay of Eq. (14) and that of Eq. (15) is that, in the former case, a $u\bar{u}$ pair is created from the vacuum, whereas, in the latter case, a $d\bar{d}$ pair is created.

VI. PARTIAL DECAY WIDTHS

In calculating the decay widths of the predicted pentaquark states (see Table VI), we adopted an effective Lagrangian for the PNJ/ψ couplings from Ref. [13] as follows:

$$\mathcal{L}^{3/2^-}_{PNJ/\psi} = i\bar{P}_\mu\left[\frac{g_1}{2M_N}\Gamma^-_\nu N\right]\psi^{\mu\nu} - i\bar{P}_\mu\left[\frac{ig_2}{(2M_N)^2}\Gamma^-\partial_\nu N + \frac{ig_3}{(2M_N)^2}\Gamma^- N\partial_\nu\right]\psi^{\mu\nu} + \text{H.c.}, \tag{16}$$

where P is the pentaquark field with spin parity $J^{\mathrm{P}} = \frac{3}{2}^-$, and N and ψ are the nucleon and the J/Ψ fields, respectively. The Γ matrices are defined as follows:

$$\Gamma^-_\nu = \begin{pmatrix} \gamma_\nu\gamma_5 \\ \gamma_\nu \end{pmatrix}, \qquad \Gamma^- = \begin{pmatrix} \gamma_5 \\ \mathbf{1} \end{pmatrix}. \tag{17}$$

As noticed by Wang *et al.* [14], the momenta of the final states in the pentaquark decays into $J/\psi p$ are fairly small compared with the nucleon mass. Thus, the higher partial wave terms proportional to $(p/M_N)^2$ and $(p/M_N)^3$ can be neglected; we can therefore consider only the first term in Eq. (16). This approximation leads to the following expression for the $P^{0+}(4377)$ partial decay width in the NJ/ψ channel [19]:

$$\Gamma(P^{0+} \to NJ/\psi) = \frac{\bar{g}_{NJ/\Psi}{}^2}{12\pi}\frac{p_N}{M_{P^{0+}}}(E_N + M_N)[2E_N(E_N - M_N) + (M_{P^{0+}} - M_N)^2 + 2M^2_{J/\psi}], \tag{18}$$

with

$$\bar{g}_{NJ/\Psi} = \frac{g_1}{2M_N}. \tag{19}$$

The kinematic variables E_N and p_N in Eq. (18) are defined as $E_N = (M_P^2 + M_N^2 - M^2_{J/\psi})/(2M_P)$ and $p_N = \sqrt{E_N^2 - M_N^2}$.

Unfortunately, as the branching ratio $\mathcal{B}(P^+ \to J/\Psi p)$ is not yet known, the coupling constant g_1 of Eq. (19) is unknown. However, our pentaquark mass predictions can provide an expression of the partial decay widths for the pentaquark states with open strangeness. For example, the P^{1+} partial decay width in the $\Sigma^+ J/\Psi$ channel is given by

$$\Gamma(P^{1+} \to \Sigma^+ J/\psi) = \frac{\bar{g}_{\Sigma^+ J/\Psi}{}^2}{12\pi}\frac{p_{\Sigma^+}}{M_{P^{1'}}}(E_{\Sigma^+} + M_{\Sigma^+}) \times [2E_{\Sigma^+}(E_{\Sigma^+} - M_{\Sigma^+}) + (M_{P^{1+}} - M_{\Sigma^+})^2 + 2M^2_{J/\psi}], \tag{20}$$

TABLE VII. Partial decay width expressions for $\Lambda J/\Psi$, $\Sigma J/\Psi$, and $\Xi J/\Psi$ channels.

Initial state	Channel	Partial width [MeV]
$P^{1'0}$	$\Lambda J/\Psi$	$0.78\Gamma_{NJ/\Psi}$
P^{1-}, P^{10}, P^{1+}	$\Sigma J/\Psi$	$0.71\Gamma_{NJ/\Psi}$
P^{2-}, P^{20}	$\Xi J/\Psi$	$0.62\Gamma_{NJ/\Psi}$

and the coupling constant $\bar{g}_{\Sigma^+ J/\Psi}$ is

$$\bar{g}_{\Sigma^+ J/\Psi} = \frac{g_1}{2M_{\Sigma^+}}. \tag{21}$$

The expressions for the partial decay widths of the $\Lambda J/\Psi$, $\Sigma J/\Psi$, and $\Xi J/\Psi$ channels are listed in Table VII.

Since the pentaquark states have been observed in the $J/\Psi p$ channel, it is natural to expect that they can be produced in $J/\Psi p$ photoproduction via the s- and u-channel process. Wang *et al.* [14] calculated the cross section of the pentaquark states in J/Ψ photoproduction and compared it with the available experimental data [20–22]. The coupling between $J/\Psi p$ and the two pentaquark states is extracted by assuming that the decay width of each pentaquark state into $J/\Psi p$ is 5% of the total width [14]. As a result, they found that if one assumes that the $J/\Psi p$ channel saturates the total width of the two pentaquark states [that is, $\mathcal{B}(P^+ \to J/\Psi p) = 1$], one significantly overestimates the experimental data. In conclusion, they found that to be consistent also with the available photoproduction data, the branching ratio for both the pentaquark states needs to be $\mathcal{B}(P^+ \to J/\Psi p) \leq 0.05$.

Thus, if we use the upper branching ratio limit extracted by Wang *et al.* [14], that is, $\mathcal{B}(P^+ \to J/\Psi p) = 0.05$, we obtain that the $P_c(4380)$ partial decay width for the $J/\psi p$ channel is

$$\Gamma_{NJ/\Psi} = \mathcal{B}(P^+ \to J/\Psi p)\Gamma_{\text{tot}} = 10.25\ \text{MeV}, \tag{22}$$

where Γ_{tot}, as reported by the LHC_b Collaboration, is 205 MeV. The numerical results for the other channels are listed in Table VIII.

TABLE VIII. Partial decay widths for $\Lambda J/\Psi$, $\Sigma J/\Psi$, and $\Xi J/\Psi$ channels. The partial decay widths are calculated from the constraint that the $J/\Psi p$ channel accounts for 5% of the total pentaquark width, as calculated by Wang *et al.* in [14].

Initial state	Channel	Partial width [MeV]
$P^{1'0}$	$\Lambda J/\Psi$	7.94
P^{1-}, P^{10}, P^{1+}	$\Sigma J/\Psi$	7.21
P^{2-}, P^{20}	$\Xi J/\Psi$	6.35

VII. CONCLUSIONS

The LHC_b Collaboration recently reported the observation of two exotic structures in the $J/\Psi p$ channel [1], which they referred to as charmonium pentaquark states (with a quark content $uudc\bar{c}$); this observation has been further supported by another two articles by the same collaboration [2,3]. The significance of each of these states is more than 9 standard deviations. The lightest one, $P_c^+(4380)$, has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the heaviest, $P_c^+(4450)$, has a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments, according to the LHC_b Collaboration [1], are $3/2^-$ and $5/2^+$, respectively.

The earliest prediction of a charmonium pentaquark state with $J^P = \frac{3}{2}^-$ was provided by Wu *et al.* [23].

The heaviest state, $P_c^+(4450)$, was apparently well explained by means of a molecular approach [4,6]; it was also predicted before the LHC_b observation by Xiao in a coupled-channel unitary approach [24].

Molecular models have also been proposed for the lightest pentaquark state, $P_c^+(4380)$, but the predictions are not so good as for the heaviest one [4,6]. The mass and the quantum numbers of the lightest state were predicted by Yuan *et al.* in 2012 [25], but these predictions depend strongly on the particular interaction used: color-magnetic interaction (CM) based on one-gluon exchange, chiral interaction (FS) based on meson exchange, and instanton-induced interaction (Inst.) based on the nonperturbative QCD vacuum structure.

In the present study, we focused on describing the lightest resonant state $P_c^+(4380)$ by means of a multiquark approach. We found that the lightest pentaquark state observed by the LHC_b Collaboration, $P_c^+(4380)$, belonged to an $SU_f(3)$ octet $[21]_8$.

Moreover, we extended the original GR mass formula [15] in order to compute the masses of the octet-pentaquark states.

The theoretical mass of the lightest pentaquark state observed by LHC_b, as predicted by the GR mass formula extension, is $M = 4377 \pm 49$ MeV, in agreement with the experimental mass, $M = 4380 \pm 8 \pm 29$ MeV.

In addition, we predicted other pentaquark states belonging to the same $SU_f(3)$ multiplet as the observed state, $P_c^+(4380)$; we also calculated their masses and suggested possible bottom baryon decay channels which involve the predicted pentaquark structures as intermediate states.

Finally, we computed the partial decay widths for all the suggested octet-pentaquark decay channels suggested.

As the $\Lambda_b \to J/\Psi K^- p$ decay is expected to be dominated by $\Lambda^* \to K^- p$ resonances [1], poor knowledge of the Λ^* excited states can affect the estimation of the parameters of the two pentaquark resonances. Moreover, as was noticed by Wang *et al.* [14], if the two pentaquark candidates are genuine states, their production in photoproduction should be a natural expectation. For these reasons, on the one hand, it is important to increase our knowledge of the missing excited states Λ^* through new experiments [26], in order to improve the analysis and to extract the masses and widths of the two pentaquarks more precisely. On the other hand, a refined measurement of the cross section of J/Ψ in photoproduction would provide more information about the nature of the pentaquark states.

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