Prediction of the masses and decay processes of strange, charmed and bottomed pentaquarks from the linear molecular crypto-heptaquark model.

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In this paper the masses and decay processes of several new strange, charmed and bottomed exotic pentaquarks are predicted. Multiquarks are studied microscopically in a standard quark model. In pure ground-state pentaquarks the short-range interaction is computed and it is shown to be repulsive. The long-range and medium-range interactions are not expected to provide sufficient attraction. An additional quark-antiquark pair is then considered, and this is suggested to produce a narrow linear molecular system. The quarks assemble in three hadronic clusters, and the central hadron provides stability. The possible crypto-heptaquark hadrons with exotic pentaquark flavours, with any number of strange, charmed and bottomed quarks, are listed. Several new exotics may still be observed.

I. INTRODUCTION

In this paper the masses and decay processes of several new strange, charmed or bottomed exotic pentaquarks are predicted in the linear-molecule heptaquark approach.

Exotic multiquarks are expected since the early works of Jaffe [1], and the masses and decays in the SU(3) exotic anti-decuplet were first predicted within the chiral soliton model [2]. The pentaquarks have been revived by several searches of the Θ+(1540) [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39], first discovered at LEPS [40, 41, 42, 43], and by recent searches of the Ξ−̅(1860) and of the D∗−̅ p(3100), respectively at NA49 [34, 35, 36, 37, 38, 39] and at H1 [40, 41, 42, 43]. Presently the number of negative experiments is larger than the number of positive experiments. For example the recent CLAS higher statistics analysis contradicts previous CLAS and ELSA experiments. Nevertheless the positive experiments don’t allow us to exclude the pentaquarks, but they show that the pentaquarks can only be produced in certain processes. In particular, recent new experiments, by SVD-2 and LEPS [28, 29, 30, 31] continue to confirm the Θ+ pentaquark. A new Θ−̅ pentaquark was also discovered recently at STAR [32, 33], which suggests that the pentaquark may have Isospin 1 or 2 [40]. If this is confirmed, the theoretical pentaquark models predicting isospin 0 for the Θ would be ruled out. Experimental upgrades are already programmed to further scan the pentaquarks. Pentaquark structures have also been studied in the lattice [44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60]. In the range of the Θ+ experimental mass, quenched lattice simulations only identify a parity - system, compatible with an open Kaon-nucleon channel. Pentaquarks motivate this effort, because they may be the first exotic hadrons ever discovered, with quantum numbers that cannot be interpreted as a quark-plus-antiquark meson or as a three-quark baryon. Importantly, the observed pentaquarks have an extremely narrow decay width, two orders of magnitude smaller than normal hadronic decay widths.

It is also remarkable that many different models presently dispute the interpretation of these multiquarks. It is well known that the pentaquark cannot be a simple five quark state in the groundstate, because it would freely recombine and decay in a Kaon and a nucleon, resulting in resonance with a very broad decay width. Thus all plausible models essentially propose an excitation which limits the decay width of the pentaquark. Because the models of non-pertubative hadronic physics are not yet sufficiently accurate or properly calibrated to describe with an excellent precision five-particle (or more) states, there is still room for different theoretical models. Examples of different models are the chiral soliton model of Diakonov, Petrov and Polyakov with a rotational excitation in the pseudoscalar field [2], the antitriplet diquark model of Jaffe and Wilczek, Karliner and Lipkin with a p-wave excitation [61, 62], and the heptaquark model of PB and Marques, applied in this paper, of Llanes-Estrada, Oset and Mateu, and of Kishimoto and Sato [63, 64, 65], or tri-linear-molecular model, with a quark-antiquark excitation. More experimental data on the pentaquarks are necessary to test the different models.

Moreover the observation of the D∗−̅ p(3100) at H1 [40] and the observation of double-charmed baryons at SELEX [66], and the expected search of double-charmed baryons at COMPASS [67] suggest that many new pentaquarks with one or two heavy quarks may still be discovered. Multiquarks are indeed favoured by the presence of several different flavours [68, 69]. In this paper I perform a systematic exploration of pentaquarks with any possible combination of flavours. For different searches, see references [70, 71, 72, 73, 74].

Here, multiquarks are studied microscopically in a standard quark-model (QM) Hamiltonian. Any multi-quark state can be formally decomposed in combinations of simpler colour-singlet clusters, the baryons and mesons. The energy of the multiquark state is computed

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with the multiquark matrix element of the QM Hamiltonian. These matrix elements also produce the short range interaction of the mesonic or baryonic subclusters of the multiquark. However, in the case of any pure exotic groundstate pentaquark, the short-range interaction can be shown to be repulsive \[1, 2, 7, 2, 7, 3, 70\]. This repulsion agrees with the quenched lattice simulations, which in the range of the \( \Theta^+ \) experimental mass, only identify a parity - system, compatible with an open Kaon-nucleon channel.

To search for attraction, one should also study other cluster-cluster interactions. For instance in the \( N + N \) system, the attractive long-range One-Pion-Exchange-Potential and the medium-range Sigma-Exchange Potential are crucial for the binding of the deuteron. In a microscopic quark Hamiltonian perspective these interactions are equivalent to the coupling to a channel with an extra pion (\( ^3S_1 \) quark-antiquark cluster) plus a \( p \)-wave excitation, and to a second channel with two extra \( s \)-wave pions respectively. Because the long range interaction is vanishing or small, and the medium range interaction may be insufficient to provide all the desired attraction, the five-quark systems are too unstable to produce narrow pentaquarks.

Nevertheless, one may consider that an \( s \)-wave flavoursinglet light quark-antiquark pair \( \bar{u}l \) is added to the pentaquark \( M \). When the resulting heptaquark \( M' \) remains bound, it is a state with parity opposite to the original \( M \) \[80\], where the reversed parity occurs due to the intrinsic parity of fermions and anti-fermions. The ground-state of \( M' \) is also naturally rearranged in an \( s \)-wave baryon and in two \( s \)-wave mesons, where the two outer hadrons are repelled, while the central hadron provides stability. The mass of the heptaquark \( M' \) is expected to be slightly lower than the exact sum of these standard hadron masses due to the binding energy. Because the \( s \)-wave pion is the lightest hadron, the minimum energy needed to create a quark-antiquark pair can be as small as 100-200 MeV. This energy shift is lower than the typical energy of 300-600 MeV of spin-isospin or angular excitations in hadrons. Therefore, the first excitation of multiquarks is quark-antiquark creation. Moreover, the heptaquarks \( M' \) may only decay into a low-energy \( p \)-wave channel (after the extra quark-antiquark pair is annihilated), resulting in a very narrow decay width, consistent with the observed exotic flavour pentaquarks. The \( M' \) is then a linear molecular system, light and with a narrow width.

In very recent works this principle was used to indicate that the \( \Theta^+ \) (1540) is probably a \( K \cdot \pi \cdot N \) molecule with binding energy of 30 MeV \[63, 64, 65\], and the \( \Xi^- \) (1862) is a \( K \cdot N \cdot \bar{K} \) molecule with a binding energy of 60 MeV \[63, 51\]. I also suggest that the new positive parity scalar \( D_{s2} \) (2320) and axial \( D_{s1} \) (2460) are \( K \cdot D \) and \( K \cdot D^* \) multiquarks \[52\], in agreement with the independent models of Barnes, Close and Lipkin and of Terasaki \[54, 56, 57\], and that the \( D^* \) (3100) is consistent with a \( D^* \cdot \pi \cdot N \) linear molecule with an energy of 15 MeV above threshold. Assuming this description of the presently observed pentaquarks, I now predict all possible exotic strange, charmed and bottomed pentaquarks compatible with the linear-molecule model.

In Section II the exotic baryon-meson short-range \( s \)-wave interaction is studied. I find repulsion in exotic multiquarks, and attraction in the channels with quark-antiquark annihilation. In Section III the possible hadrons with exotic pentaquark flavours are qualitatively studied with an additional quark-antiquark pair. This study includes pentaquarks with any number of strange, charmed and bottomed quarks. I find that several new exotics may still be observed. In section IV the conclusion is presented.

### II. THE ATTRACTION/REPULSION CRITERION

The standard QM Hamiltonian is,

\[
H = \sum_i T_i + \sum_{i<j} V_{ij} + \sum_{ij} A_{ij},
\]

see Fig. 1. Each quark or antiquark has a kinetic energy \( T_i \). The colour-dependent two-body interaction \( V_{ij} \) includes the standard QM confining and hyperfine terms,

\[
V_{ij} = \frac{3}{16} \vec{x}_i \cdot \vec{x}_j \left[ V_{\text{conf}}(r) + V_{\text{hyp}}(r) \vec{S}_i \cdot \vec{S}_j \right].
\]

The potential of eq. 2 reproduces the meson and baryon spectrum with quark and antiquark bound states (from
heavy meson decay channels

...couplings of four wavefunctions. For example the RGM product of two wavefunctions is replaced by a product of four wavefunctions. Variational method for the Schrödinger equation, where overlaps are similar to the matrix elements occurring in the interaction can be decomposed in RGM overlaps. The potentials in eq. (1) are unimportant, only their matrix elements are constrained when the quark model produces spontaneous chiral-symmetry breaking. The annihilation potential is present in the π Salpeter equation, where the π is the only hadron with a large negative-energy wavefunction, $\phi^- \sim \phi^+$. In eq. (6) the annihilation potential $A$ cancels most of the kinetic energy and confining potential $2T + V$. This is the reason why the pion has a very small mass. From the hadron spectrum and using eq. (7), the matrix elements of the annihilation potential are determined as,

$$<2T + V | A | 2T + V> \propto (\phi^+ \phi^-) = M_{\pi} \left( \phi^+ \phi^- \right),$$

where the $\pi$ is the only hadron with a large negative-energy wavefunction, $\phi^- \sim \phi^+$. In eq. (6) the annihilation potential $A$ cancels most of the kinetic energy and confining potential $2T + V$. This is the reason why the pion has a very small mass. From the hadron spectrum and using eq. (7), the matrix elements of the annihilation potential are determined as,

$$<2T + V | S = 0 | 2T + V> \propto \frac{2}{3}(2M_N - M_\Delta),$$

$$\Rightarrow |A| S = 0 \propto \frac{2}{3}(2M_N - M_\Delta),$$

which is correct for the annihilation of $u$ or $d$ quarks, and nearly correct for the $s$ quark.

The annihilation potential only shows up in non-exotic channels, and it is clear from eq. (7) that the annihilation potential provides an attractive (negative) interaction. The quark-quark(antiquark) potential is dominated by the interplay of the hyperfine interaction of eq. (4) and the quark exchange of eq. (4). In s-wave systems with low spin this results in a repulsive interaction. The short-range interactions are independent of the details of the chiral-invariant quark model that one chooses to consider. Therefore, I arrive at the attraction/repulsion criterion for groundstate hadrons:

- whenever the two interacting hadrons have quarks (or antiquarks) with a common flavour, the repulsion is increased by the Pauli principle;
- when the two interacting hadrons have a quark and an antiquark with the same flavour, the attraction is enhanced by the quark-antiquark annihilation.
TABLE II: Masses and decay processes of exotic flavour pentaquarks with one heavy quark. The method to arrive at this table is described in Section III. The possible resonances are divided in classes characterized by the flavour of light $l = u, d$ or strange $s$ quarks (antiquarks), and the number or heavy $H = c, b$ quarks (antiquarks).

| linear molecule | mass [GeV] | decay channels |
|-----------------|------------|----------------|
| $I = 1/2$, $H s l l l l$ : four-hadron molecule | | |
| $K \cdot \Lambda \cdot K$ | $3.23 \pm 0.03$ | $\bar{K} + \Xi_c, \pi + \Omega_c$ |
| $K \cdot \Lambda \cdot \bar{K}$ | $6.57 \pm 0.03$ | $\bar{K} + \Xi_b, \pi + \Omega_b$ |
| $I = 3/2$, $H s l l l l l$ : five-hadron molecule | | |
| $K \cdot \Lambda \cdot l l$ | $3.25 \pm 0.03$ | $\bar{K} + \Sigma_c, D + \Sigma_c, \pi + \Xi_c$ |
| $K \cdot N \cdot D$ | $3.39 \pm 0.03$ | $\bar{K} + \Sigma_c, D^* + \Sigma_c, \pi + \Xi_c$ |
| $K \cdot N \cdot \bar{B}$ | $6.66 \pm 0.03$ | $\bar{K} + \Sigma_b, \bar{B} + \Sigma_b, \pi + \Xi_b$ |
| $K \cdot N \cdot B^*$ | $6.71 \pm 0.03$ | $\bar{K} + \Sigma_b, B^* + \Sigma_b, \pi + \Xi_b$ |

For instance, $uud - su$ is attractive, and $uud - us$ is repulsive. In the cases where attraction is added to repulsion, it turns out that attraction prevails when there are more quark-antiquark matchings than quark-quark ones. For example, $uss - s\bar{s}$ is attractive whereas $ss\bar{s} - s\bar{s}$ is repulsive. This qualitative rule is confirmed by quantitative computations of the short-range interactions of the $\pi, N, K, D, D^*, B, B^*$. This rule can also be applied to other baryons. I find for example that the $\pi \Lambda$ short-range interaction is vanishing, while the $I = 3/2, K \cdot \Sigma$ interaction is repulsive.

III. EXOTIC-FLAVOUR PENTAQUARKS

The exotic pentaquarks containing five quarks only are not expected to bind, due to the attraction/repulsion criterion. To increase binding we include a light $ll$ quark-antiquark pair in the system. I now detail the strategy to find the possible linear leptaquark molecules.

a) I consider any leptaquark with the flavour of an exotic pentaquark and with up to two heavy flavours or antiflavours. Hadrons with three heavy flavour are presently quite hard to produce in the laboratory. The top quark is excluded because it is too unstable. To minimise the short-range repulsion and to increase the attraction of the three-hadron system, I only consider pentaquarks with a minimally exotic isospin, and with low spin.

b) Here the flavour is decomposed in an $s$-wave system of a spin 1/2 baryon and two pseudoscalar mesons, except for the vectors $D^*$ and $B^*$ which are also considered.

c) I only consider, as candidates for narrow pentaquarks, the systems where at least one hadron is attracted by both other ones. The attraction/repulsion criterion is used to discriminate which hadrons are bound and which are repelled.

d) In the case of some exotic flavour pentaquarks, only a four-hadron-molecule or a five-hadron-molecule would bind. These cases are not detailed in the tables, because they are difficult to create in the laboratory.

e) Moreover, in the particular case where one of the three hadrons is a $\pi$, binding is only assumed if the $\pi$ is the central hadron, attracted both by the other two ones. The $\pi$ is too light to be bound by just one hadron.

f) The masses of the bound states with a pion are computed assuming a total binding energy of the order of $10$ MeV, averaging the binding energy of the $\Theta^+$ and of the $D^* + \rho$ system in the molecular perspective. The masses of the other bound states are computed assuming a total binding energy of the order of $50$ MeV, averaging

TABLE III: Masses and decay processes of exotic flavour pentaquarks with one heavy anti-quark. The method to arrive at this table is described in Section III. The possible resonances are divided in classes characterized by the flavour of light $l = u, d$ or strange $s$ quarks (antiquarks), and the number or heavy $H = c, b$ quarks (antiquarks).

| linear molecule | mass [GeV] | decay channels |
|-----------------|------------|----------------|
| $I = 0$, $s s s \bar{H}(+3ll)$ : five-hadron molecule | | |
| $D \cdot \pi \cdot \Xi$ | $3.31 \pm 0.03$ | $D + \Xi, D_8 + \Lambda$ |
| $D^* \cdot \pi \cdot \Xi$ | $3.45 \pm 0.03$ | $D^* + \Xi, D^*_8 + \Lambda, D_8 + \Lambda$ |
| $B \cdot \pi \cdot \Xi$ | $6.73 \pm 0.03$ | $B + \Xi, B_8 + \Lambda$ |
| $B^* \cdot \pi \cdot \Xi$ | $6.77 \pm 0.03$ | $B^* + \Xi, B^*_8 + \Lambda, B_8 + \Lambda$ |
| $I = 1/2$, $s l l l / l l l l$ : five-hadron molecule | | |
| $D \cdot \pi \cdot \Sigma$ | $3.19 \pm 0.03$ | $D + \Lambda, D + \Sigma, D_8 + N$ |
| $D^* \cdot \pi \cdot \Sigma$ | $3.33 \pm 0.03$ | $D^* + \Lambda, D^* + \Sigma, D^*_8 + N$ |
| $B \cdot \pi \cdot \Sigma$ | $6.60 \pm 0.03$ | $B + \Lambda, B + \Sigma, B_8 + N$ |
| $B^* \cdot \pi \cdot \Sigma$ | $6.64 \pm 0.03$ | $B^* + \Lambda, B^* + \Sigma, B^*_8 + N$ |

| linear molecule | mass [GeV] | decay channels |
|-----------------|------------|----------------|
| $I = 0$, $l l l l / l l l l$ : five-hadron molecule | | |
| $D \cdot \pi \cdot N$ | $2.93 \pm 0.03$ | $D + N$ |
| $D^* \cdot \pi \cdot N = D^* \rho$ | $3.10$ | $D^* + N, D + N$ |
| $B \cdot \pi \cdot N$ | $6.35 \pm 0.03$ | $B + N$ |
| $B^* \cdot \pi \cdot N$ | $6.39 \pm 0.03$ | $B^* + N, B + N$ |
TABLE IV: Masses and decay processes of exotic flavour pentaquarks with two heavy quarks. The method to arrive at this table is described in Section IIII. The possible resonances are divided in classes characterized by the flavour of light $l = u, d$ or strange $s$ quarks (antiquarks), and the number or heavy $H = c, b$ quarks (antiquarks).

| linear molecule | mass [GeV] | decay channels |
|-----------------|------------|----------------|
| $I = 1/2$, $H H_{ssl}(+l l)$ = $H l l + H l l$ | 5.00 ± 0.03 | $D + \Omega_c$, $\bar{K} + \Omega_{cc}$ |
| $D \otimes \Xi \otimes D$ | 5.14 ± 0.03 | $D(D'^*) + \Omega_c$, $\bar{K} + \Omega_{cc}$ |
| $D' \otimes \Xi \otimes D^*$ | 5.29 ± 0.03 | $D + \Omega_c$, $\bar{K} + \Omega_{cc}$ |
| $D \otimes \Xi \otimes \bar{B}(\bar{B}^*)$ | 8.41 (8.46) ± 0.03 | $D + \Omega_b$, $\bar{B}(\bar{B}^*) + \Omega_c$ |
| $D' \otimes \Xi \otimes \bar{B}(\bar{B}^*)$ | 8.56 (8.60) ± 0.03 | $D' + \Omega_b$, $\bar{B}(\bar{B}^*) + \Omega_c$ |
| $B = \Xi \otimes \bar{B}(\bar{B}^*)$ | 11.87 (11.92) ± 0.03 | $\bar{B}(\bar{B}^*) + \Omega_b$, $\bar{K} + \Omega_{bb}$ |
| $B_3 = \Xi \otimes \bar{B}(\bar{B}^*)$ | 11.87 (11.92) ± 0.03 | $\bar{B}(\bar{B}^*) + \Omega_b$, $\bar{K} + \Omega_{bb}$ |
| $I = 1/2$, $H H_{ssl}(+l l)$ = $s l l + H l l$ | 5.42 ± 0.1 | $K + \Omega_{cc}, D + \Omega_c$ |
| $K \otimes \Xi_{cc}$ | 7.77 (11.02) ± 0.1 | $\bar{K} + \Omega_{cc}, D + \Omega_c$ |
| $I = 1$, $H H_{ssl}(+l l)$ = $H l l + H l l$ | 4.80 ± 0.03 | $D + \Xi_c$, $\bar{K} + \Xi_{cc}$, $\bar{\pi} + \Xi_{cc}$ |
| $D \otimes \Lambda \otimes D$ | 4.94 ± 0.03 | $D(D'^*) + \Xi_c$, $\bar{K} + \Xi_{cc}$ |
| $D' \otimes \Lambda \otimes D^*$ | 5.08 ± 0.03 | $D' + \Xi_c$, $\bar{K} + \Xi_{cc}$ |
| $D \otimes \Lambda \otimes \bar{B}(\bar{B}^*)$ | 8.21 (8.26) ± 0.03 | $D + \Xi_b$, $\bar{B}(\bar{B}^*) + \Xi_c$ |
| $D' \otimes \Lambda \otimes \bar{B}(\bar{B}^*)$ | 8.35 (8.40) ± 0.03 | $D' + \Xi_b$, $\bar{B}(\bar{B}^*) + \Xi_c$ |
| $B = \Lambda \otimes \bar{B}(\bar{B}^*)$ | 11.62 (11.67) ± 0.03 | $\bar{B}(\bar{B}^*) + \Xi_b$, $\bar{K} + \Xi_{bb}$ |
| $B_3 = \Lambda \otimes \bar{B}(\bar{B}^*)$ | 11.67 (11.72) ± 0.03 | $\bar{B}(\bar{B}^*) + \Xi_b$, $\bar{K} + \Xi_{bb}$ |
| $I = 3/2$, $H H_{SSL}(+l l)$ = $H l l + H l l$ | 8.01 (8.06) ± 0.03 | $\bar{B}(\bar{B}^*) + \Xi_c$, $\Xi_{bb} + \bar{K}$ |
| $B(\bar{B}^*) \otimes \Lambda \otimes \bar{K}$ | 7.94 (8.08) ± 0.1 | $D(D'^*) + \Xi_b$, $\Xi_{bb} + \bar{K}$ |
| $I = 0$, $H H_{lll}(+l l)$ = $ll l + ll l$ | 4.62 ± 0.03 | $D + \Sigma_c$, $\bar{\pi} + \Xi_{cc}$ |
| $D \otimes \Lambda \otimes D$ | 4.76 ± 0.03 | $D + \Sigma_c$, $D' + \Sigma_c$ |
| $D' \otimes \Lambda \otimes D^*$ | 4.91 ± 0.03 | $D' + \Sigma_c$, $\bar{\pi} + \Xi_{cc}$ |
| $D \otimes \Lambda \otimes \bar{B}(\bar{B}^*)$ | 8.04 (8.08) ± 0.03 | $D + \Xi_b$, $\bar{B}(\bar{B}^*) + \Sigma_c$ |
| $D' \otimes \Lambda \otimes \bar{B}(\bar{B}^*)$ | 8.18 (8.22) ± 0.03 | $D' + \Sigma_b$, $\bar{B}(\bar{B}^*) + \Sigma_c$ |
| $B \otimes \Lambda \otimes \bar{B}(\bar{B}^*)$ | 11.45 (11.49) ± 0.03 | $\bar{B}(\bar{B}^*) + \Sigma_b$, $\bar{\pi} + \Xi_{bb}$ |
| $B_3 \otimes \Lambda \otimes \bar{B}(\bar{B}^*)$ | 11.49 (11.54) ± 0.03 | $\bar{B}(\bar{B}^*) + \Sigma_b$, $\bar{\pi} + \Xi_{bb}$ |
| $I = 0$, $H H_{lls}(+l l)$ = $l s l + l l H$ | 4.20 ± 0.1 | $K + \Sigma_{cc}$, $D + \Lambda_c$ |
| $K \otimes \Xi_{cc}$ | 7.45 (10.70) ± 0.1 | $K + \Xi_{cc}, D + \Lambda_c$ |
| $K \otimes \Xi_{lll}(\Xi_{bb})$ | 7.94 (8.08) ± 0.03 | $K + \Xi_{cc}, \bar{B}(\bar{B}^*) + \Lambda_c$ |

the binding energies of the $\Xi^{-*}$ and of the new positive-parity $D_{s2}$ mesons.

g) For a more precise binding energy one would need to include the attractive medium-range interaction, the full three-body Faddeev effects, and the coupling to p-wave decay channels. Nevertheless all these effects increase the binding energy, without changing the heptauquark picture of this result. This results in an error

bar of $\pm 30$ MeV for the mass of the multiquark. When one of the hadrons in the molecule is not listed by the Particle Data Group [97], the hadron mass is extracted from a recent lattice computation [38], and the error bar for the mass of the multiquark is $\pm 100$ MeV.

h) Although three-body decay channels are possible through quark rearrangement, their observation requires high experimental statistics. Only some of the different possible two-body decay processes are detailed here.

The possible narrow exotic-flavour pentaquarks are summarised in Tables II, III, IIII, XXX and XXXV. For each flavour the heptauquark structure is produced, and the possible molecular states are listed together with the possible two-body decay processes. Three-body decays may also be possible, but they are not detailed here. For isospin $I \neq 0$ the decay processes are shown in a condensed form. For instance, the $\Xi^{-}$ observed at NA49 [33] belongs to an iso-quadruplet, and in Table II the decay process is summarised into $\bar{K} + \Sigma$, where $K$ corresponds to either $K^+$ or to $K^0$ while $\bar{K}$ corresponds either to $K^-$ or $K^0$. When the isospin is specified, the different members of the quadruplet decay respectively to $K^- + \Xi^-$, to $K^- + \Xi^0$ and $K^0 + \Xi^+$, to $K^- + \Xi^-$ and $K^0 + \Xi^0$,
and to $\bar{K}^0 + \Xi^+$. Moreover, Tables IV and V have a very large number of states, and therefore these tables are further condensed when at least one of the heavy quarks is a bottom quark. For instance, $B(B^*)$ means that both $B$ and $B^*$ states should be considered.

IV. CONCLUSION AND OUTLOOK

This work has performed a systematic search of exotic-flavour pentaquarks, using the linear three-body hadronic-molecule perspective. This perspective is the result of standard QM computations of pentaquarks masses and of hadron-hadron short-range interactions. This view, where the quark-antiquark annihilation is crucial, explains the difficulty of quenched lattice QCD computations in identifying the positive parity pentaquark $0^+$. I only consider pentaquarks with an extra light $\bar{Q}$ quark-antiquark pair (total parity $+$), minimal exotic isospin, and spin $1/2$. These are the most favourable conditions to have exotic pentaquarks, but nevertheless more exotic states may still be observed. Because quark models are not fully calibrated yet, the results are affected by an error bar.

A large number of new exotic flavour-pentaquarks are predicted in Tables I, II, III, IV and V together with their decay channels. It is interesting to remark that degenerate states occur in Tables III and IV and in Tables III and V.

Moreover, some new multiquarks are easier to bind than the presently observed exotic pentaquarks. In particular two very promising new exotic-flavour pentaquark candidates are the $I = 1/2$, $sll[\bar{s}l]c = N \bullet \bar{K} \bullet D$ and $sll[\bar{s}l]c = N \bullet \bar{K} \bullet D^*$ states. Notice that the $D_s(2317)$ might be a $I = 0$, $\bar{K} \bullet D$ state, the $D_s(2460)$ might be a $I = 0$, $\bar{K} \bullet D^*$ state with 60 MeV binding energies, $\Sigma_2 \Sigma_3 \Sigma_4 \Sigma_5$, and that the $\Lambda(1405)$ may also be a $I = 0$, $N \bullet K$ with binding energy of 30 MeV (mixed with a $\Sigma \bullet \pi$ state) $\bar{D}_K^{100}$. This particular pentaquark candidate is thus expected to have a large binding energy, of the order of 100 MeV, possibly larger than the binding energy of the other resonances of its class. Moreover the $\pi$, the $\bar{K}$, the $N$ and the $D^*$ can be detected by most experimental collaborations. Thus these two resonances, with masses of the order of respectively 3.20 to 3.25 GeV and 3.34 to 3.39 GeV, decaying into the two-body decays listed in Table III and also in three-body decays, say in $D(D^*) + \pi + \Sigma$ are excellent candidates for new pentaquarks. If one of these new resonances is observed, it will provide an excellent evidence for hadronic molecules.

The quantitative computation of the masses, decay rates and sizes of some of the proposed heptaquarks will be done elsewhere. The most relevant contributions that remain to be included in this framework are the attractive medium-range interaction, the full three-body Fadeev effects, and the coupling to p-wave decay channels.

Acknowledgments

I am grateful to Katerina Lipka, Achim Geiser, Paula Bordalo and Pedro Abreu for discussions on the possibility to detect new exotic pentaquarks. This work is devoted to encourage the experimental search for new exotic multiquarks.

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