Simple estimates of the masses of pentaquarks with hidden beauty or strangeness

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Abstract

The masses of cryptoexotic pentaquarks with hidden beauty are estimated phenomenologically using the results by the LHCb collaboration which discovered recently the cryptoexotic pentaquarks with hidden charm. The expected masses of the hidden beauty pentaquarks are about 10.8 GeV and 10.7 GeV in the limit of some kind of heavy quark symmetry. The states with hidden strangeness considered in similar way have masses about 2.37 GeV and 2.30 GeV, by several hundreds of MeV higher than states discussed previously in connection with the relatively light positive strangeness pentaquark \( \theta^+ \). Empirical data on spectra of pentaquarks can be used to get information about quarkonia interaction with nucleons. The results obtained for the case of heavy flavors are in fair agreement with model of isospin (pion) exchange between flavored baryons and anti-flavored vector mesons, proposed by Karliner and Rosner, and in qualitative agreement with the bound state version of the chiral soliton model.

1 Introduction

Recent remarkable observation of the pentaquark baryon states with hidden charm and the quark content \( c\bar{c}uud \) with masses 4450 MeV and 4380 MeV \cite{1,2,3} provided new impact for studies of baryon pentaquark states, which have been almost stopped lately. The pentaquarks have been observed in \cite{1} as Breit-Wigner resonances in the system nucleon — charmonium \( J/\psi \). This means that there is enough interaction between \( J/\psi \)-meson and the nucleon, although the branching for the decay \( P_c \rightarrow J/\psi p \) was not measured, and other possible decay modes have not been studied.

Such decay modes are, e.g. \( P_c \rightarrow \bar{D}^0 \Lambda_c^+ \), or \( P_c \rightarrow \bar{D}^0 \Sigma_c^+ \), and \( P_c \rightarrow D^- \Sigma_c^{++} \), and their branching can be considerably greater than branching of the decay \( P_c \rightarrow J/\psi p \) which has highly efficient dimuon trigger due to decay \( J/\psi \rightarrow \mu^+ \mu^- \). The Breit-Wigner resonance structure should be seen in these modes, quite similar to the case of \( P_c \rightarrow J/\psi p \). The LHCb collaboration is going to study these decay modes which contain two charmed particles, although they do not expect to see very many events in these decays with the current data sample \cite{1}.

The mass of these pentaquark states is mainly due to the masses of heavy charmed quark and antiquark. A natural question is what could be the masses of analogous cryptoexotic pentaquarks with hidden beauty, which have the quark content \( b\bar{b}uud \) or \( b\bar{b}udd \). The simplest possible assumption...
is that such pentaquarks also are similar resonances in the system \( \Upsilon - \) nucleon, and their masses also are mainly due to masses of heavy bottom quark and antiquark.

Here we present a very simple estimate of masses of cryptoexotic pentaquarks with hidden beauty, in assumption that the states observed in [1] are indeed pentaquarks (not some threshold or another kinematical effect), and that structure of the hidden beauty pentaquark is similar to the structure of the hidden charm pentaquark [1].

Similar estimates can be made also for cryptoexotic pentaquarks with hidden strangeness (in this case the strange quarkonium, or strangeonium, is the \( \phi(1020) \) meson). The resulting masses are by several hundreds of MeV higher than masses of such states discussed previously [4, 5, 6, 7]. To make these estimates we assume that similaity of the quarkonia interaction with nucleons takes place. Such similarity of strangeonium, charmonium and bottomonium has been pointed out in [8] for the case of meson dynamics. These estimates, being straightforward and almost trivial, may have nontrivial consequences after observation of the pentaquark states with hidden flavor, beauty and strangeness. Unique information about quarkonia interactions with nucleons could be extracted from these data.

2 Masses of pentaquarks from masses of quarkonia

The simplest estimate of the pentaquarks masses with hidden beauty, i.e. containing the \( \bar{b}b \) pair, is the following ([9] and comment by the author to this article)

\[
M(P_b) = M(P_c) + M(\Upsilon) - M(J/\psi),
\]

where \( M(\Upsilon) = 9460 \) MeV is the mass of the lightest bottomonium, \( M(J/\psi) = 3097 \) MeV is the charmonium mass, and we obtain

\[
M(P_b, 1) = 10743 \text{ MeV}
\]

the mass of lighter hidden beauty - pentaquark,

\[
M(P_b, 2) = 10813 \text{ MeV}
\]

the mass of heavier pentaquark.

This estimate is in the spirit of the heavy quarks symmetry, discussed previously, see e.g. [10] and references in this paper. It is supposed here that the role of charmonium and bottomonium in formation of cryptoexotic pentaquarks is approximately the same, see discussion below.

Similar estimates can be made for the pentaquarks with hidden strangeness.

\[
M(P_s) = M(P_c) + M(\phi) - M(J/\psi),
\]

where \( M(\phi) \simeq 1020 \) MeV is the \( \phi \)-meson mass. We obtain then

\[
M(P_s, 1) = 2303 \text{ MeV,} \quad M(P_s, 2) = 2373 \text{ MeV}
\]

for the masses of the lower and higher hidden strangeness pentaquarks.

These relations can be written in the form connecting differences of pentaquark masses with differences of masses of corresponding quarkonia:

\[
M(P_b) - M(P_c) = M(\Upsilon) - M(J/\psi); \quad M(P_c) - M(P_s) = M(J/\psi) - M(\phi).
\]

These contributions of the heavy quark masses obviously satisfy these relations, but do the quark and gluon sea contribution satisfy, or not - this is just a question. At the next step we can include
into consideration the difference in the kinetic energies of the motion of the pentaquarks constituents - quarkonium and nucleon. We ascribe the difference of pentaquark masses and the quarkonium mass plus the nucleon mass to the kinetic energy of the constituents motion. The reduced mass\(^2\) of the \(J/\psi\) meson and nucleon is about 721 MeV, for the \(\Upsilon(9460)\) and nucleon it is 854 MeV; for the \(\phi\)-meson and nucleon it is about 489 MeV. As a result, the masses of hidden beauty pentaquarks decrease slightly, but masses of hidden strangeness pentaquarks increase by about \(\sim 200\) MeV, see the table.

|       | \(P_c(1)\) | \(P_c(2)\) | \(P_b(1)\) | \(P_b(2)\) | \(P_s(1)\) | \(P_s(2)\) |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|
| \(HQS\) | 4450(input) | 4380(input) | 10813       | 10743       | 2373        | 2303        |
| \(\text{kin.en.corr.}\) | 4450       | 4380       | 10748       | 10689       | 2565        | 2466        |
| \(\text{threshold}\) | 4462       | 4462       | 11139       | 2085        |

**Table.** The masses of cryptoexotic states with hidden charm (input, taken from [1]), hidden beauty and strangeness. First line of numbers — the limit of heavy quarks symmetry. Next line of numbers — the difference in kinetic energies is taken into account. In the last line the thresholds are indicated for states consisting of corresponding \(\Sigma\)-baryon and flavored vector meson (\(\bar{D}^*(2009), B^*(5325),\) or \(\bar{K}^*(892)\)).

Note, that masses of cryptoexotic pentaquark states with hidden strangeness obtained in this way are considerably - by several hundreds of MeV - greater than masses of similar states discussed previously in connection with possible observation of the positive strangeness pentaquark \(\theta^+(1540)\) [4, 5, 6, 7]. A review of experimental situation with observation/nonobservation of this low mass positive strangeness pentaquark is presented e.g. in [12], where it is called a "mystery". The most recent high statistics experiment to search for \(\theta^+\) in the reaction \(\pi^- p \to K^- X\) [13] provided negative result for the mass interval \((1.44 - 1.58)\) GeV. Discussion of theoretical status of relatively light pentaquarks within the chiral soliton models can be found in [14, 15].

The difference of the quarkonium mass and twice the mass of lightest meson with corresponding flavor is \(m_\phi - 2m_{K^+} \approx 32\) MeV for strangeness, \(m_{J/\psi} - 2m_{D^+} \approx -642\) MeV for charm, and \(m_\Upsilon - 2m_{B^+} \approx -1098\) MeV for beauty. This illustrates the difference of the sea contributions to the masses of quarkonia for different flavors. We assumed that same differences in the sea of quark and gluons contributions take place for the masses of pentaquarks with hidden flavor, and this crucial assumption will be checked when the masses of the hidden strangeness and beauty pentaquarks will be established.

Further refinements are of interest and possible, in particular, the difference of interactions of different quarkonia with nucleons may be included into consideration, see e.g. [16, 17, 18, 19]. This may demand considerable efforts, because direct measurements of this difference are not possible in view of absence of the quarkonia beams. On the other hand, detection and studies of cryptoexotic hidden flavors pentaquarks could provide information on different quarkonia interactions with nucleons, which is difficult to obtain in other ways. The comparisons with other approaches, discussed below, are of interest.

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\(^2\)The reduced mass in the system of two particles with masses \(m_1, m_2\) is \(m_{12} = m_1 m_2 / (m_1 + m_2)\), the kinetic energy of their relative motion in the center of mass system is \(\vec{p}_1^2 / m_1 + \vec{p}_2^2 / m_2 = \vec{p}^2 / m_{12}\), i.e. inversely proportional to the reduced mass at fixed momentum \(\vec{p}\).

\(^3\)It should be mentioned here that the name \(\theta^+\) has been proposed by D.I.Diakonov for the low mass positive strangeness pentaquark seen by several collaborations in 2002 - 2004. In calculation [5] the mass of \(\theta^+(1540)\) has been used as input. The rough estimates of the pentaquark masses, as well as masses of exotic baryon systems made in [11] as a function of the "exotiness" number \(m\) (number of additiona quark-antiquark pairs) gave the values of the \(m = 1\) pentaquark masses higher by few hundreds of MeV - about 1 GeV above the nucleon mass, see Eq. (6), end of section 2 in [11].
3 Comparison with the molecular type models

A natural way to estimate the masses of pentaquarks is to consider them as dynamically generated in meson-baryon interactions \[20\] or as a molecular-type bound states of baryons and mesons, as it was made in \[21, 22, 23, 24\]. Several states with hidden charm and masses above 4 GeV have been predicted in \[20\] where the decay channel \( P_c \to J/\psi p \) also has been pointed out as convenient for detection of this particle. As in our case, for heavy flavors the relative accuracy of such estimates is better than for lighter flavors. The hidden charm states have been obtained as \( \Lambda_c \) (or \( \Sigma_c \)) — \( \bar{D} \) (\( \bar{D}^* \)) molecules, and similar for hidden bottom states. This approach allowed to make more detailed predictions of binding energies, and it is not in contradiction with our simple estimates. Several states with hidden beauty and masses around 11 GeV have been obtained in \[22\] as result of meson (\( B, B^* \)) baryon (\( \Lambda_b, \Sigma_b, \Sigma_b^* \)) interactions due to exchange of vector mesons.

The isovector meson (pion) exchange binding mechanism has been proposed in \[23\], which could provide binding of the \( \Sigma_c \bar{D}^* \) state (threshold energy 4462.4 MeV) in fair agreement with observation of \[1\]. There are no bound states containing \( \Lambda_c \) or \( \Lambda_b \) in this approach because of isospin properties of the pion exchange. Similar estimates for hidden strangeness pentaquarks would be of interest. If we are building the pentaquark states from the octet of baryons and the nonet of vector mesons, we shall obtain antidecuplet and \( \{27\} \)-plet of pentaquarks. The isospin zero \( \theta^+ \in \mathbf{10} = (K^{*+}n_1 - K^{*0}p)/\sqrt{2} \), \( \theta^{*+} \in \{27\} = K^{*+} p \), etc. The masses of these states are expected to be smaller than threshold energy \( \sim 1830 \) MeV.

4 Remarks on the bound state chiral soliton model

As we mentioned already, dramatic events took place around observation/nonobservation of the relatively light positive strangeness pentaquark predicted just within a variant of the chiral soliton model in \[4\]. Several years yearlier the crude estimate of the pentaquark masses provided the values about 1 GeV above the nucleon mass \[11\], even without the flavor symmetry breaking mass term contributions. Here we show that phenomenological estimates we made in section 2 are in qualitative agreement with the bound state version of the chiral soliton model, first proposed for description of exotic heavy flavored states in \[25\] and recently discussed in \[10\].

The chiral soliton approach is conceptually different from approaches discussed in previous section, because each state is characterized by external quantum numbers, but the constituents (building blocks) of the state do not come into play at all. In such models the flavor/antiflavor excitation energies are equal \[26, 27, 29\]

\[
\omega_F = \frac{N_c}{8\Theta_F} (\mu_F - 1); \quad \bar{\omega}_F = \frac{N_c}{8\Theta_F} (\mu_F + 1)
\]

where \( N_c \) is the number of colors of the underlying QCD, \( \Theta_F \) is the so called flavored moment of inertia
of skyrmion, $\Gamma$ is proportional to the $\Sigma$- term of the nucleon (it is the "rigid oscillator" version of the model proposed by Klebanov and Westerberg [26, 27]; definitions and slightly modified complete formulas can be found in [29] and references in this paper).

$$\mu_F = \frac{1}{N_c} \left[ N_c^2 + 16\Theta_F \left( \bar{m}_D^2 \Gamma + (F_D^2 - F_\pi^2)\tilde{\Gamma} \right) \right]^{1/2}$$  \hspace{1cm} (5)

is dimensionless quantity with

$$\bar{m}_D^2 = \frac{F_D^2}{F_\pi^2} m_D^2 - m_\pi^2.$$  \hspace{1cm} (6)

$m_D$ is the $D-$ meson (or $B-$ meson, or $K$-meson) mass, $F_D$ is the corresponding meson decay constant, e.g. $F_K/F_\pi \simeq 1.22$, $F_D/F_\pi \simeq 1.58$ [28].

At large enough mass $m_D$ we have approximately

$$\mu_F \simeq 4\bar{m}_D \sqrt{\frac{\Gamma\Theta_F}{N_c}}$$  \hspace{1cm} (7)

and

$$\omega_F \simeq \frac{F_D}{F_\pi} m_D \sqrt{\frac{\Gamma}{4\Theta_F}}$$  \hspace{1cm} (8)

Since we have always $\Gamma/4\Theta_F < 1$ [29], the quantity

$$\epsilon_F = m_D \left[ 1 - \frac{F_D}{F_\pi} \sqrt{\frac{\Gamma}{4\Theta_F}} \right]$$  \hspace{1cm} (9)

can be interpreted as a binding energy of the heavy meson by skyrmion.

For cryptoexotic states the sum enters

$$\omega_F + \omega_\bar{F} = \frac{N_c}{4\Theta_F} \mu_F \simeq \frac{F_D}{F_\pi} m_D \sqrt{\frac{\Gamma}{\Theta_F}}$$  \hspace{1cm} (10)

which defines the main contribution to the difference of masses of the pentaquark and nucleon. Relations (7) – (10) work better for heavy flavors, charm or beauty, for the case of charm (10) gives the value about 3.31 GeV, for reasonable choice of the model parameters, see [29], in agreement with data [1], and somewhat greater than the mass of the $J/\psi$-quarkonium. For beauty the knowledge of the ratio $F_B/F_\pi$ is lacking still. If we take this ratio equal to that for charm, we obtain from (10) the value $9.35$ GeV $^4$, which gives the mass of the $P_b$ pentaquark about $10.29$ GeV (lower boundary), in fair agreement with estimates of section 2.

For strangeness the result from Eq. (5) for the sum of energies (10) is about $0.84$ GeV, by $0.18$ GeV lower than the mass of the $\phi$-meson. It is lower than estimate made above in section 2, and close to previous estimate [11], but spin and isospin dependent corrections should be included as well. Relations (9), (10) are of interest because they connect quantities of different nature: flavor decay constants $F_D$, $F_\pi$, skyrmions characteristics $\Gamma$, $\Theta_F$ and the masses of hadrons. Spin and isospin dependent hyperfine splitting correction to the energy of the state should be included for more detailed comparison with data [26, 29], this will be done elsewhere.

Within the chiral soliton approach the exotic (also nonexotic) states naturally belong to definite $SU(3)$ multiplets of baryons — antidecuplet [4], {27}–plet or {35}–plet [5]. The states we discuss}

$^4$For these estimates we used the values $\Gamma = 4.83 GeV^{-1}$, $\tilde{\Gamma} = 15.6 GeV^{-1}$, $\Theta_F^0 = 2.04 GeV^{-1}$, $\Theta_c = \Theta_F^0 + (F_D^2/F_\pi^2 - 1)\Gamma/4 = 3.85 GeV^{-1}$, see [29] and references in this paper.
here most probably are the partners of the lowest states which belong to definite SU(3) multiplets, discussed in section 7 of [15]b. They can be some mixtures of the components of different SU(3) multiplets, and this point needs further clarification.

5 Conclusions and prospects

We have estimated the masses of pentaquarks with hidden flavor, beauty and strangeness, using a simplified phenomenological model of the bound state of quarkonium and nucleon. These estimates may be useful for planning future experiments and as starting point of more refined study. The spectra of such states will be a source of information about quarkonia — nucleons interaction and about flavor dependence of the quarks and gluon sea contribution to the pentaquark masses. In view of uncertainties intrinsic to the model and the way of calculation we pretend on the qualitative agreement with data, only.

The results obtained within the bound state version of the chiral soliton model (section 4) are in reasonable agreement with data for the hidden charm pentaquark [1] and support the phenomenological estimate of section 2 for the mass of hidden beauty pentaquark. It would be important and very interesting to find and study manifestly exotic baryon states, i.e. with negative charm, or positive strangeness or beauty, to complete the picture of baryons exotics.

The pentaquark states with hidden flavors appear naturally in the molecular-type models where the pentaquark consists of flavored baryon and anti-flavored meson, vector [22] or pseudoscalar [23, 24]. The point is that in isospin exchange models [23], and in our estimates the masses of hidden strangeness states turn out to be higher than masses of states discussed previously in connection with supposed existence of the relatively light positive strangeness pentaquark \( \theta^+ \) [4, 5, 6, 7].

Few days after this paper has been submitted to HEP database (arXiv:1510.05958 [hep-ph]), the paper [30] appeared where the possibility to detect the pentaquarks with hidden strangeness in decays of \( \Lambda_c^{+}(2286) \to P_s^{+}\pi^0 \to \phi p\pi^0 \), which is analogous to the discovery channel of \( P_c^{+} \) [1], \( \Lambda_b \to P_c^{+}K^- \to J/\psi pK^- \), was pointed out. This possibility could be realized only if the mass of \( P_s^{+} \) is low enough, smaller than \( \sim 2151 \) MeV. The possibilities to detect the states with masses 2372 MeV and 2303 MeV, indicated here after Eq. (2) and in the table above, have been discussed in version 3 of paper [30].

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