Estimates of the masses of pentaquarks with hidden beauty or strangeness

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Remarkable observation of the pentaquark baryon states with hidden charm and the quark content $c\bar{c}uud$ with masses:

$M_{P_c}(4450) = (4449.8 \pm 1.7 \pm 2.5)$ **MeV,** $\Gamma = (39 \pm 5 \pm 19)$ **MeV, (12 st. dev.), and**
$M_{P_c}(4380) = (4380 \pm 8 \pm 29)$ **MeV,** $\Gamma = (205 \pm 18 \pm 86)$ **MeV, (9 st. dev.),**
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$$\Lambda_b^0 \to P_c K^-$$

$$P_c \to J/\psi\, p$$

$P_c\,(c\bar{c}\,uud)$ **observed as Breit-Wigner resonances in the system nucleon - charmonium** J/ψ**.**

The branching for the decay $P_c \to J/\psi\, p$ **was not measured. Other possible decay modes should be observed:**

$$P_c \to \bar{D}^0\,\Lambda_c^+$$

or

$$P_c \to \bar{D}^0\,\Sigma_c^+, \quad P_c \to D^-\,\Sigma_c^{++},$$

their branching can be considerably greater than branching of the decay $P_c \to J/\psi\, p$ **which has efficient dimuon trigger due to decay** $J/\psi \to \mu^+\mu^-$**. The Breit-Wigner resonance structure should be seen in these modes, quite similar to the case of** $P_c \to J/\psi\, p$**.**

A natural Q is what could be the masses of analogous cryptoexotic pentaquarks with hidden beauty ($b\bar{b}uud$ **or** $b\bar{b}udd$**)**
and strangeness ($s\bar{s}uud$ **and** $s\bar{s}\,udd$**).**
Such pentaquarks also can be similar resonances in the system Υ **- nucleon, (**ϕ**-meson - nucleon); for beauty their masses also are mainly due to masses of heavy quark and antiquark.**

The prospect of hadrons with more than the minimal quark content ($q\overline{q}$ or qqq) was proposed by Gell-Mann in 1964 [1] and Zweig [2], followed by a quantitative model for two quarks plus two antiquarks developed by Jaffe in 1976 [3]. The idea was expanded upon [4] to include baryons composed of four quarks plus one antiquark; the name pentaquark was coined by Lipkin [5]. Past claimed observations of pentaquark states have been shown to be spurious [6], although there is at least one viable tetraquark candidate, the $Z(4430)^+$ observed in $\overline{B}^0 \to \psi' K^- \pi^+$ decays [7–9], implying that the existence of pentaquark baryon states would not be surprising. States that decay into charmonium may have particularly distinctive signatures [10].

Large yields of $\Lambda_b^0 \to J/\psi K^- p$ decays are available at LHCb and have been used for the precise measurement of the Λ_b^0 lifetime [11]. (In this Letter mention of a particular mode implies use of its charge conjugate as well.) This decay can proceed by the diagram shown in Fig. 1(a), and is expected to be dominated by $\Lambda^* \to K^- p$ resonances, as are evident in our data shown in Fig. 2(a). It could also have exotic contributions, as indicated by the diagram in Fig. 1(b), that could result in resonant structures in the $J/\psi p$ mass spectrum shown in Fig. 2(b).

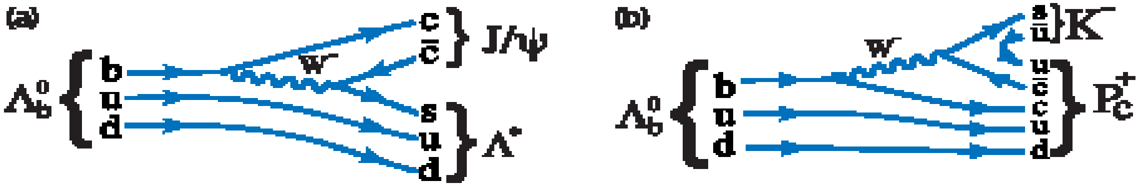


Figure 1: Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

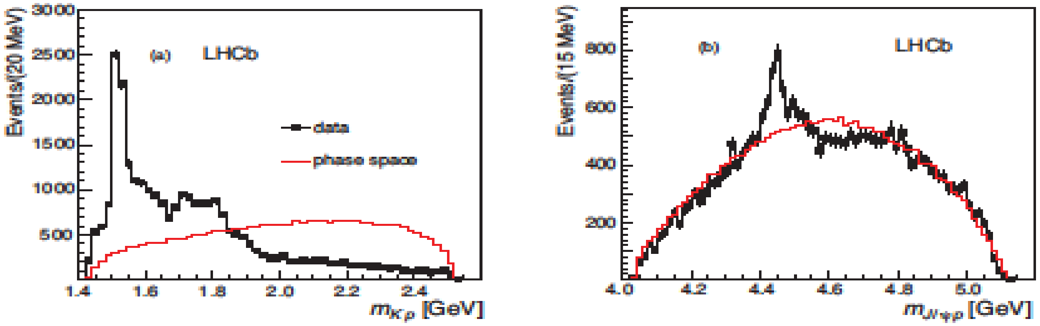


Figure 2: Invariant mass of (a) $K^- p$ and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

Masses of pentaquarks from masses of quarkonia

The simplest estimate of the pentaquarks masses with hidden beauty, i.e. containing the $b\bar{b}$ pair, is the following (VK, 2015)

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

where $M(\Upsilon) = 9460\,MeV$ - mass of the lightest bottomonium, $M(J/\psi) = 3097\,MeV$ is the charmonium mass, so

$$M(P_b, 1) = 10743\,MeV$$

the mass of lighter hidden beauty - pentaquark,

$$M(P_b, 2) = 10813 MeV$$

the mass of heavier pentaquark.

This estimate is in the spirit of the heavy quarks symmetry, discussed previously, (N.Scoccola, D.Riska) It is supposed here that the role of charmonium and bottomonium in formation of cryptoexotic pentaquarks is approximately the same, see discussion below.

Similar, fot the P_q with hidden strangeness:

$$M(P_s) = M(P_c) + M(\phi) - M(J/\psi), \tag{2}$$

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

$$M(P_s, 1) = 2303\,MeV, \qquad M(P_s, 2) = 2373\,MeV$$

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

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. The reduced mass of the quarkonium meson and the nucleon comes into play. As a result, the masses of hidden beauty pentaquarks decrease slightly, but masses of hidden strangeness pentaquarks increase by about $\sim 200\,MeV$. More refined treatment demands the knowledge of the quarkonia - nucleon interaction, lacking still.

	$P_c(1)$	$P_c(2)$	$P_b(1)$	$P_b(2)$	$P_s(1)$	$P_s(2)$
HQS	4380(input)	4450(input)	10743	10813	2303	2373
$kin.en.corr.$	4380	4450	10689	10748	2466	2565
$threshold$	4462		11139		2085	

Table. The masses of cryptoexotic states with hidden charm (input, taken from LHCb1), hidden beauty and strangeness. First line — the limit of heavy quarks symmetry. Next line — the difference in kinetic energies is taken into account. In the last line the thresholds are indicated for states consisting of corresponding Σ-baryon and flavored vector meson ($\bar{D}^*(2009)$, $B^*(5325)$, or $\bar{K}^*(892)$).

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

Masses of $P_q - s$ with hidden strangeness obtained in this way are considerably - by hundreds of MeV - greater than masses of similar states discussed previously in connection with the positive strangeness pentaquark $\theta^+(1540)$ (DPP,1987; H.Walliser, VK, 2003).

Candidates for hidden strangeness pentaquarks have been proposed in 2005 by Arndt, Azimov, M.Polyakov, Strakovsky, Workman. Masses of N^* candidates 1680 MeV and 1730 MeV.

The difference of the quarkonium mass and twice the mass of lightest meson with corresponding flavor is

$m_\phi - 2m_{K+} \simeq 32\,MeV$ for strangeness,

$m_{J/\psi} - 2m_{D+} \simeq -642\,MeV$ for charm,

$m_\Upsilon - 2m_{B+} \simeq -1098\,MeV$ 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.

Further refinements are possible and are of interest, in particular, the difference of interactions of different quarkonia with nucleons may be included into consideration. 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.

Comparison with the molecular type models

Early redictions of nonminimal states (tetraquarks, pentaquarks) were made in '70-th in quark models: **Jaffe, 1976; Okun, Voloshin, 1976; Strottman, 1979; Lipkin, 1987**.

A natural way to estimate the masses of pentaquarks is to consider them as dynamically generated in meson-baryon interactions or as a molecular-type bound states of baryons and mesons. Several states with hidden charm and masses above $4\,GeV$ have been predicted in
Wu, Molina, Oset, Zou: Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV Phys.Rev.Lett. 105 (2010) 232001),
$M(P_c) = 4269$ MeV, or 4418 MeV, the decay channel $P_c \to J/\psi\, p$ also has been pointed out as convenient for detection of this particle. For heavy flavors the relative accuracy of such estimates is better than for lighter flavors.

The isovector meson (pion) exchange binding mechanism has been proposed in
Karliner, Rosner: New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules. Phys.Rev.Lett. 115 (2015) 12, 122001. It provides binding of the $\Sigma_c \bar{D}^*$ state (threshold energy $4462.4\,MeV$ in fair agreement with observation of LHCB1. There are no bound states containing Λ_c or Λ_b in this approach because of isospin properties of the pion exchange.

Similar estimates for hidden strangeness pentaquarks would be of interest.
The molecular-type hidden strangeness pentaquarks consisting of Σ-hyperon and $\bar{K}^*$ meson should have the mass not greater than corresponding threshold, about $2085\,MeV$, also greater than results obtained previously within the chiral soliton approach (DPP), but smaller than estimates made above.

Remarks on the bound state chiral soliton model

There were different predictions of pentaquarks in chiral soliton model: Diakonov, Petrov, Polyakov, 1997: low mass, narrow positive stramgeness $\theta^+(1540)$, not seen now. Most recent high statistics experiment **Naruki et al, JPARC E19 Collab, 2015**.

More than 6 years before this (VK, NORDITA preprint 90/55; Phys Lett B259 (1991) 234) rough estimate within CSM: $M(P_s) - M(N) >\sim 1\, GeV$. No definite predictions for the components of antidecuplet.

Riska and Scoccola, 1993 - anti-charmed and anti-bottom baryons were found to be stable for strong interactions.

The model proposed by **Klebanov, Westerberg, 1994** - rigid oscillator model - especially simple and transparent. For cryptoexotic states the sum enters

$$M(P_F) - M_N \sim \omega_F + \omega_{\bar F} = \frac{N_c}{4\Theta_F}\mu_F \simeq \frac{F_D}{F_\pi} m_D \sqrt{\frac{\Gamma}{\Theta_F}}$$

Flavor (antiflavor) excitation energies:

$$\omega_F = \frac{N_c}{8\Theta_F}(\mu_F - 1); \quad \omega_{\bar F} = \frac{N_c}{8\Theta_F}(\mu_F + 1)$$

where N_c is the number of colors of the underlying QCD, Θ_F is the so called flavored moment of inertia of skyrmion, Γ is proportional to the $\Sigma-$ term of the nucleon.

$M(P_F) - M_N$ is close to the mass of the quarkonium (these relations are valid for heavy flavors, charm or beauty, but should be modified for strangeness). For charm it is $\simeq 3.3\, GeV$ for reasonable choice of the model parameters.

For beauty this contribution is 9.35 GeV, which leads to $M(P_b) >\sim 10.3$ GeV. These relations are of interest because they connect quantities of differen nature: flavor decay constants F_D, F_π 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.

a) $J^P(exp)[4450,\ 4380] = \left[\frac{5}{2}^+,\ \frac{3}{2}^-\right]$**;**

b) $J^P(exp)[4450,\ 4380] = \left[\frac{5}{2}^-,\ \frac{3}{2}^+\right]$**;**

c) $J^P(exp)[4450,\ 4380] = \left[\frac{3}{2}^-,\ \frac{5}{2}^+\right]$**;**

$I = 1/2,\ J = 5/2$ **provides a challenge for the CSA, because**

$J = I^R$ **within the CSA.**

Conclusions and prospects

(*) Discovery of the hidden charm pentaquarks provided desired progress in studies of the hadron structure.

(*) Observation of P-s with hidden beauty and strangeness and comparison with simple estimates would be of great interest. Information about interaction of quarkonia with nucleons could be extracted.

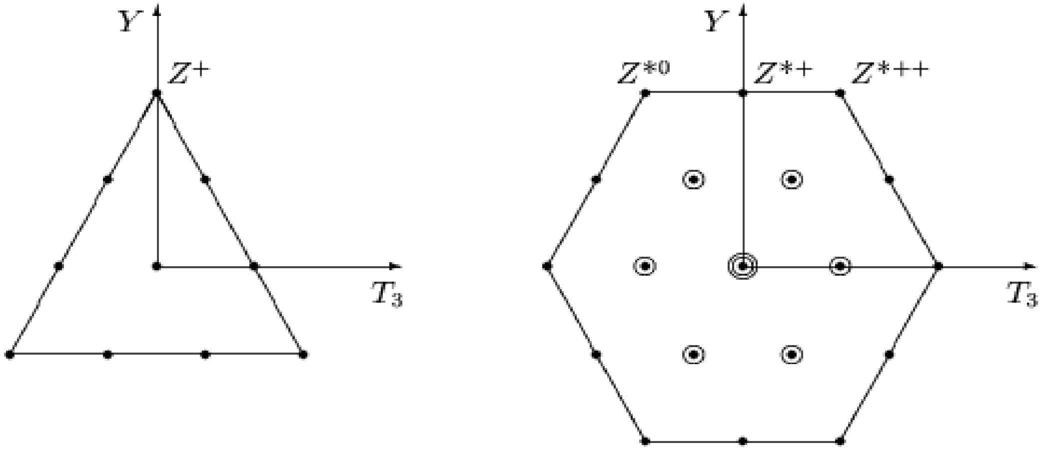
(*) Observation of manifestly exotic states with positive strangeness (beauty), negative charm remains to be an actual experimental task.

(*) Meausered quantum numbers of pentaquarks (isospin and spin) provide a challenge for the CSA ($SU(3)$ multiplets ?).

a naive Skyrme model the estimate $M_{\{\overline{10}\}} - M_{\{8\}} \simeq 0.60$ GeV [5] was obtained, according to (7). The mass of the $\{27\}$ lies then $\simeq 0.10$ GeV higher. In Fig. 1 we show the spectrum of all baryon multiplets with an excitation energy up to 2.5 GeV using these moments of inertia for illustration. The sequence of the lowest baryon multiplets

$$\{8\}\, J = \frac{1}{2}\,,\;\; \{10\}\, J = \frac{3}{2}\,,\;\; \{\overline{10}\}\, J = \frac{1}{2}\,,\;\; \{27\}\, J = \frac{3}{2}\,,\;\; \{35\}\, J = \frac{5}{2}\;\ldots \tag{8}$$

turns out to be unique within a large range of moments of inertia $\Theta_\pi/3 < \Theta_K < \Theta_\pi/2$, covering many realistic cases. Diagrams for the lowest non-minimal baryon multiplets $\{\overline{10}\}$ and $\{27\}$ which accomodate the interesting $S = +1$ states are depicted in Fig. 2.



$\{\overline{10}\}\ J = 1/2$

$\{27\}\ J = 3/2$

Figure 2: The $T_3 - Y$ diagrams for the baryon multiplets $\{\overline{10}\}$ and $\{27\}$ which include the lowest $S = +1$ states.

So far we have considered the $SU(3)$ symmetric case. In order to explain the