# Penta-quark States with Strangeness, Hidden Charm and Beauty

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The classical quenched quark models with three constituent quarks provide a good description for the baryon spatial ground states, but fail to reproduce the spectrum of baryon excited states. More and more evidences suggest that unquenched effects with multi-quark dynamics are necessary ingredients to solve the problem. Several new hyperon resonances reported recently could fit in the picture of penta-quark states. Based on this picture, some new hyperon excited states were predicted to exist; meanwhile with extension from strangeness to charm and beauty, super-heavy narrow  $N^*$  and  $\Lambda^*$  resonances with hidden charm or beauty were predicted to be around 4.3 and 11 GeV, respectively. Recently, two of such  $N^*$  with hidden charm might have been observed by the LHCb experiment. More of those states are expected to be observed in near future. This opens a new window in order to study hadronic dynamics for the multi-quark states.

KEYWORDS: Penta-quark, Hadron spectroscopy, Multi-quark state

## 1. Introduction

Correct description of hadron spectrum is one of the most important ways to understand the strong interaction governed by the Quantum chromodynamics (QCD) theory. For example, through the discovery of ground baryons, such as proton, neutron,  $\Delta(1232)$ ,  $\Sigma$ ,  $\Xi$  and so on, the classical three-quark constituent model was built to describe various ground baryons, and successfully predicted  $\Omega(sss)$  baryon which was confirmed by later experiments with the mass around 1670 MeV. In classical constituent quark models, hadrons are ascribed as baryon composed of three-quarks and meson composed of a quark-antiquark pair. In these models, ground states are that each quark is in S-wave of orbital angular momentum (L=0) and radial ground state (n=0), while excited states are those with at least one of the quantum numbers of (L,n) is larger than 0. Thus the lowest excitation of baryon is (L,n) = (1,0), and their total spin and parity are  $J^p = \frac{1}{2}^-$ .

As we known, even for the lowest excited hadron states, spectra predicted from the classical quark models are not consistent with observations of various experiments. For example, the lowest negative parity baryons are  $N^*(1535)$  and  $\Lambda^*(1405)$  with  $J^p = \frac{1}{2}^-$  [1]. However, the three-quark model expects that  $N^*(1535)$  with  $|uud\rangle$  is lighter than  $\Lambda^*$  with  $|uds\rangle$ . Furthermore, it also expects  $N^*(1535)$  is lighter than  $N^*(1440)$  which is considered as the first radially state of nucleon with  $J^p = \frac{1}{2}^+$ . In fact, the  $N^*(1535)$  is heavier than both  $\Lambda^*(1405)$  and  $N^*(1440)$ . This is the long-standing mass order reverse problem for the three lowest excited baryons. For the meson sector, the same thing is happening. The scalar nonet with  $J^p = 0^+$  including  $f_0(500)$ ,  $\kappa(600 - 800)$ ,  $a_0(980)$  and  $f_0(980)$ , is the lowest excited meson nonet (L=1). However,  $f_0(500)$ ,  $\kappa(600-800)$  and  $f_0(980)$  are all lighter than their vector partner,  $\omega(782)$ ,  $K^*(892)$  and  $\phi(1020)$ . In the classical  $q\bar{q}$  model,  $f_0(500)$  and  $a_0^0(980)$  are regarded as

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 $(u\bar{u}+d\bar{d})/\sqrt{2}$  and  $(u\bar{u}-d\bar{d})/\sqrt{2}$ , while  $f_0(980)$  is  $s\bar{s}$  state. As a result, this model cannot explain why the mass of  $a_0^0(980)$  degenerates with  $f_0(980)$  rather than close to  $f_0(500)$ . In summary, the classical constituent quark models cannot explain the excited hadron spectrum. It implies new components are needed to describe hadrons. In this paper, we focus on the baryon sector.

In the QCD field, the multi-quark component is not forbidden because  $q\bar{q}$  can be dragged out from the glue field, in other words, the number of constituent quarks in a hadron is not a constant. This new picture can be named as unquenched quark model, while original picture is quenched quark model. Since multi-quark states are available in unquenched quark models, the baryon spectrum predicted from these models will be very different from that of three-quark models. Furthermore, these multi-quark components can naturally explain the problem in the three-quark model. For instance, the mass order reverse problem is easily solved by including large penta-quark components in these baryon states [2–5].

The  $N^*(1535)$ ,  $\Lambda^*(1405)$  and  $N^*(1440)$  could have large  $|udus\bar{s}\rangle$ ,  $|udsq\bar{q}\rangle$  (q=u or d) and  $|uduq\bar{q}\rangle$  components, respectively. The higher mass of  $N^*(1535)$  is due to its large  $s\bar{s}$  component. On the other hand, the  $s\bar{s}$  component also results in its large couplings to the channels with strangeness, such as  $N\eta$ ,  $N\eta'$ ,  $N\phi$  and  $K\Lambda$ . By recent experimental data and theoretical analyses,  $N^*(1535)$  is indeed strongly coupled with these channels [1, 2, 6-10].

There are two possible ways to form penta-quark states: colored and uncolored quark cluster. The former one considers the five-quark as diquark-diquark-antiquark [11–13], where diquark is a qq colored cluster; The latter one corresponds to the meson-baryon coupled channel model [14–28], for example,  $\Lambda^*$ (1405) can be dynamically generated from the coupled channels of  $\bar{K}N$  and  $\Sigma\pi$  [29].

Both penta-quark and three-quark components may exist in baryons. For  $J^p = \frac{1}{2}^-$  baryons, to excite a constituent quark to be L=1 state and to drag out a light  $q\bar{q}$  pair from gluon field, the two different mechanisms may be comparable. Therefore, these baryons are possibly the mixtures of the three-quark and five-quark components. Then a very natural question is that how the three-quark and five-quark configurations transfer to each other? The breathing model is proposed in Refs. [13, 30], here, the mass of the lowest  $\Omega^*$  is predicted by including the  $sss \leftrightarrow sssq\bar{q}$  transition [31,32].

It needs the development from both theory and experiment sides to understand dynamics of pentaquark states. New experimental data provide us some clues to extend the existing baryon spectrum. As shown in the Particle Group Data (PDG) [1], the information of hyperon resonances is very limited. Recent measurements from CLAS [34], LEPS [33] and Crystal Ball (CB) [35, 36] provide us new information of  $\Sigma^*$  and  $\Lambda^*$  resonances. Correspondingly, analyses of these data [37,39,40] bring great changes to understand the properties of  $\Sigma^*$  and  $\Lambda^*$  resonances. All of these new changes strongly support unquenched models. In order to go beyond the large mixture between three-quark and five-quark configurations, we used the hidden charm and beauty components to replace the light  $q\bar{q}$  pair in the five-quark configurations [41,42]. As a result, several new  $N^*$  and  $\Lambda^*$  resonances with hidden charm and beauty are predicted with super-heavy mass and narrow width. The super-heavy mass is due to the  $c\bar{c}$  and  $b\bar{b}$  components and the narrow width stems from the small coupling between  $c\bar{c}$  or  $b\bar{b}$  and light quark pairs. If confirmed, they definitely have penta-quark component dominance. Very recently, two of such  $N^*$  with hidden charm might have been observed by the LHCb experiment in the decay of  $\Lambda_b$  [43]. More of those states are expected to be observed in near future. This opens a new window for study hadronic dynamics for the multi-quark states.

### 2. Baryon Spectroscopy with Strangeness

In Ref. [1], it lists a lot of ground and excited states of  $\Sigma$ ,  $\Xi$  and  $\Omega$  baryons. However, the well established states (marked as four-star) only include six  $\Sigma$  states, two  $\Xi$  states and one  $\Omega$  state. Especially, only ground state of  $\Omega$  is confirmed as  $\Omega(1670)\frac{3}{2}^+$ . There is no experimental determination on the quantum numbers for the excited  $\Omega$  resonances. Moreover, the  $J^P$  of the lowest excited baryon

states in the quenched quark model is  $1/2^-$ . However, for these hyperon resonances, there are no established states with this  $J^p$ . On experimental side, the measurement about these hyperon resonances are all from old experiments of 1970 – 1985 before 2005. Fortunately, there are some new observations about  $\Sigma^*$  and  $\Lambda^*$  from CLAS [34], LEPS [33] and CB group [35]. On theoretical side, the unquenched quark model provides totally different predictions of  $1/2^-$  strangeness baryons. For example, the classical quenched quark models [44] predict the  $1/2^ \Sigma^*$  and  $\Xi^*$  to be around 1650 MeV and 1760 MeV, respectively, while the unquenched quark models expect them to be around 1400 MeV and 1550 MeV [3, 4, 13], or 1450 MeV and 1620 MeV [45–47], respectively. It is necessary to check the predictions of hyperon resonances in these unquenched quark models with new data. On the other hand, each baryon might be a mixture of the three-quark and five-quark components. However, the mechanism of transition between them is not well established. Here based on the Nambu-Jona-Lasinio (NJL) model and instanton-induced interaction, the mass of the lowest  $\Omega^*$  is predicted by including not only five-quark and three-quark Hamiltonian, but also the potential of transition between them [31, 32].

#### 2.1 New analyses of CB data

In Ref. [35], differential cross sections and hyperon polarizations for  $\bar{K}^0 n$ ,  $\pi^0 \Lambda$ , and  $\pi^0 \Sigma^0$  productions in  $K^- p$  interactions at eight  $K^-$  momenta between 514 and 750 MeV/c were measured. It provides us a nice place to explore the pure isospin I=1 and 0 channels, respectively. The new combined fit of these new data with old data [38] on  $K^- n \to \pi^- \Lambda$  for the pure I=1 is performed, and for the pure I=0 channel [39], the new data of  $K^- p \to \pi^0 \Sigma^0$  are also analyzed [40]. The fit results of both two channels provide a new spectrum of  $\Sigma^*$  and  $\Lambda^*$ , which are consistent with predictions of unquenched models.

In the  $\Sigma^*$  sector, new analyses of differential cross sections and  $\Lambda$  polarizations for reactions  $K^-n\to\pi^-\Lambda$  and  $K^-p\to\pi^0\Lambda$  are performed by the effective Lagrangian method, and the experimental data are from the new high-statistic CB experiment [35] and the early report of Ref. [38], with the c.m. energy 1550-1676 MeV. In the analyses, the t-channel  $K^*$  exchange and the u-channel proton exchange amplitudes are fundamental backgrounds. The well-established four-star  $\Sigma(1189)\frac{1}{2}^+$ ,  $\Sigma^*(1385)\frac{3}{2}^+$ ,  $\Sigma^*(1670)\frac{3}{2}^-$ , and  $\Sigma^*(1775)\frac{5}{2}^-$  contributions are always included in analyses. If only including above u,t-channel backgrounds and s-channel resonances, the  $\chi^2$  of the best fit arrives 1680 for total 348 data points. Then each additional resonance of  $J^p = \frac{1}{2}^-$ ,  $\frac{1}{2}^+$ ,  $\frac{3}{2}^-$  and  $\frac{3}{2}^+$  reduces the  $\chi^2$  to 899, 572, 943, and 1392, respectively. Obviously, the data favor a  $\frac{1}{2}^+$   $\Sigma^*$  resonance with the mass of 1635 MeV. It is worthy to mention that polarizations data play the most important role, which discriminates the  $\Sigma^*(1620)\frac{1}{2}^-$  from  $\Sigma^*(1635)\frac{1}{2}^+$ . This analysis shows that  $\Sigma^*(1660)\frac{1}{2}^+$  is definitely needed, while  $\Sigma^*(1620)\frac{1}{2}^-$  is not needed at all. With the further investigation, the  $\Sigma^*\frac{1}{2}^-$  with much lower mass, as suggested by the penta-quark model [3], cannot be excluded. Therefore, there is no evidence for the  $\Sigma^*$  with  $\frac{1}{2}^-$  suggested by the quenched quark model around 1600 MeV. In addition, other  $\Sigma$  resonances may exist,  $\Sigma^*(1610)\frac{1}{2}^+$ ,  $\Sigma^*(1542)\frac{3}{2}^-$  and  $\Sigma^*(1840)\frac{3}{2}^+$ , where  $\Sigma^*(1542)\frac{3}{2}^-$  is consistent with the structure of  $\Sigma(1560)$  or  $\Sigma(1580)$  resonance in PDG [1].

In the  $\Lambda^*$  sector, the reaction  $K^-p \to \pi^0 \Sigma^0$ , as a pure I=0 process, can be used to identify the structures of  $\Lambda$  resonances. As we known, the polarization data is crucial important for analyses. However, with different data selection cuts and reconstructions, two groups in the same collaboration, i.e., the UCLA group [35] and the VA group [36], gave the very different polarization data. By fitting both two sets of the data, it is interesting to find that dropping four-star  $\Lambda(1690)\frac{3}{2}^-$  only increases  $\chi^2/N$  0.004, while dropping any other resonance will increase  $\chi^2/N$  more than 0.5. In other words, the four-star  $\Lambda(1690)\frac{3}{2}^-$  is not needed here, while at the same energy range  $\sim 1680$  MeV, there is strong evidence for the existence of a new  $\Lambda^*(\frac{3}{2}^+)$  resonance. As a result, the contribution of the new  $\Lambda^*(1680)\frac{3}{2}^+$  replaces the contribution from the four-star  $\Lambda(1690)\frac{3}{2}^-$ , which has important

implications for hyperon spectroscopy and its underlying dynamics. The lowest  $\Lambda(\frac{3}{2}^+)$  is predicted around 1900 MeV in the qqq constituent quark model [44], which is consistent with  $\Lambda^*(1890)(\frac{3}{2}^+)$  in the PDG. However, the penta-quark dynamics predicts it to be below 1700 MeV [3], which is corresponding to this new  $\Lambda^*(1680)\frac{3}{2}^+$  here.

By these two new investigations and previous researches about the  $\Sigma^*$  [49] and a new narrow

By these two new investigations and previous researches about the  $\Sigma^*$  [49] and a new narrow  $\Lambda(\frac{3}{2}^-)$  [50], new spectra of  $\Sigma^*$  and  $\Lambda^*$  are well consistent with those expected in unquenched quark models. New  $\Sigma(1380)\frac{1}{2}^-$  and  $\Sigma(1635)\frac{1}{2}^+$  are corresponding to the predictions of unquenched quark models,  $\Sigma(\frac{1}{2}^-)$  around 1360 - 1420 MeV and  $\Sigma(\frac{1}{2}^+)$  around 1630 & 1656 MeV [48], respectively. On the other hand, there is no evidence for  $\Sigma^*(\frac{1}{2}^-)$  around 1650 MeV as suggested in the quenched model. For  $\Lambda^*$  resonances, the new  $\Lambda^*(1680)\frac{3}{2}^+$  is consistent with the prediction of Ref. [3], and the new  $\Lambda^*(1670)\frac{3}{2}^-$  [50] with narrow width instead of the broad  $\Lambda(1690)\frac{3}{2}^-$  obviously cannot be explained by quenched quark models. However, together with the new  $\Sigma^*(1542)\frac{3}{2}^-$ ,  $\Lambda^*(1520)\frac{3}{2}^-$ ,  $\Lambda^*(1520)\frac{3}{2}^-$  and either  $\Xi(1620)$  or  $\Xi(1690)$ , there is a nice  $\frac{3}{2}^-$  baryon nonet with large penta-quark configuration.

It needs a completed low-lying hyperon spectrum to establish the multi-quark picture for hadronic excited states, especially the  $\frac{1}{2}^-$  and  $\frac{3}{2}^ \Sigma^*$ ,  $\Xi^*$  and  $\Omega^*$ .

## 2.2 Lowest $\Omega^*$ within $sss \leftrightarrow sssq\bar{q}$

Five quark components play an important role in the excitation of baryons. Then the excited baryon may have both qqq and  $qqqq\bar{q}$  configurations, which involves the transition between two components. The key point of transition is a correct  $q\bar{q}$  creation mechanism. However, in various models, such as  $^3P_0$  model [51], string-breaking models [52] and others [53], the  $q\bar{q}$  pair creation operator only provides the  $^3P_0$  state of  $q\bar{q}$ . However, for low-lying five-quark configurations with the negative parity, five quarks are all supposed to be relative S-wave. As a result, these  $q\bar{q}$  pair creation operators cannot contribute to the transition between qqq and  $qqqq\bar{q}$ .

In recent Refs. [31, 32], the instanton-induced interaction and NJL model are applied for new  $q\bar{q}$ pair creation mechanisms, which create  $q\bar{q}$  pairs with quantum numbers  ${}^3P_0$  and  ${}^1S_0$ . By applying these three-quark and five-quark transitions in the Hamiltonian matrix, the lowest excitation of  $\Omega$ is predicted to be around 1780 MeV with  $\frac{3}{2}$ . This result is very different from the prediction of the quenched model where the lowest  $\Omega^*$  is around 2020 MeV with relative angular momentum L=1 [54]. On the other hand, if only with the five-quark components, the lowest  $\Omega^*$  was predicted around 1820 MeV [55], and Ref. [56] also predicts the lowest  $\Omega^*$  as  $\bar{K}\Xi$  bound state around 1805 MeV. It shows that predicted mass of the lowest  $\Omega^*$  in multi-quarks models is much lighter than that in the three-quark model. It is very important to measure where is the lowest  $\Omega^*$  experimentally. Recently, the Beijing Spectrometer II (BESII) collaboration at Beijing Electron Positron Collider (BEPC) has already observed the  $\Psi(2S) \to \Omega\bar{\Omega}$  which branch ratio is  $(5 \pm 2) \times 10^{-5}$  [57]. Now with the upgraded BEPC, billions of  $\psi(2S)$  events will be collected by BESIII Collaboration [58], which is two orders of magnitude higher than what BESII experiment got. The mass upper limitation of  $\Omega^*$ in  $\Psi(2S) \to \Omega^*\Omega$  is 2030 MeV. So it is a nice place to examine the existence of the  $\Omega^*$  resonance predicted by the multi-quark models. Once the lowest  $\Omega^*$  is fixed, there will be a clear picture for the internal structure of  $\Omega^*$  states.

#### 3. From Strangeness to Charm and Beauty

As discussed in the introduction, a lot of well established  $N^*$  and  $\Lambda^*$  resonances were proposed to have large five-quark configurations, such as  $N^*(1535)$  and  $\Lambda^*(1405)$ . However, they are hard to distinguish from classical quark model states due to tunable ingredients and possible large mixing of various configurations in these models. In the PDG-2010 [59], it still claimed: "The clean  $\Lambda_c(2595)$ 

spectrum has in fact been taken to settle the decades-long discussion about the nature of the  $\Lambda(1405)$  – true 3-quark state or mere  $\bar{K}N$  threshold effect – unambiguously in favor of the first interpretation." Obviously, this claim is not justified, and it disappears in the later versions of PDG [1]. Actually, Refs. [60,61] propose the  $\Lambda_c(2595)\frac{1}{2}^-$  to be DN molecule.

Now the question is that how to distinguish three-quark and five-quark components in baryons. It is too difficult for us to answer. Then making the question simpler: where is the five-quark dominant state? Here we only consider such  $q_1q_2q_3q\bar{q}$  state where q and  $\bar{q}$  have the same flavor. Thus the exotic penta-quark states are not discussed here, such as  $\theta^+$  with  $|udud\bar{s}>$ , since up to now there is no convincing evidence for these states. A possible alternative solution of the five-quark dominant state is to extend lighter quark-antiquark pair to the heavy quark-antiquark pair. If baryons have the heavy  $Q\bar{Q}$  (Q=c,b) components, their masses will be definitely much larger than ordinary baryons composed of three light quarks, while with much narrower width. Therefore, such super-heavy baryons are definitely beyond the naive qqq consistent quark model. For example, if the  $N^*(1535)$  is the  $\bar{K}\Sigma$  quasi-bound state or  $[ud][us]\bar{s}$  diquark-diquark-antiquark state with hidden strangeness, naturally, by replacing  $s\bar{s}$  as  $c\bar{c}$  or  $b\bar{b}$ , some super-heavy  $N^*$  states with hidden charm or beauty may exist. The possible states would be strongly coupled with  $\bar{D}\Sigma_c$  and  $B\Sigma_b$  channels, respectively. In the first subsection, the predictions of such  $N^*$  and  $\Lambda^*$  resonances will be introduced. In the second subsection, we will introduce the study for searching baryons with hidden charm and beauty in experiments.

#### 3.1 Predictions of $N^*$ and $\Lambda^*$ resonances with hidden charm and beauty

By following the Valencia approach [62], the model is extended from three flavors to four. Refs. [41, 42] consider two sets of coupled-channels, pseudoscalar-baryon (PB) channels including  $\bar{D}\Sigma_c$ ,  $\bar{D}\Lambda_c$ , and  $\eta_c N$ , and vector-baryon (VB) channels including  $\bar{D}^*\Sigma_c$ ,  $\bar{D}^*\Lambda_c$ , and  $J/\psi N$ . With the interaction by exchanging vector meson, the T matrix of  $PB \rightarrow PB$  and  $VB \rightarrow VB$  can be obtained by solving the coupled channels Bethe-Salpeter (BS) equation in the Valencia approach of Ref. [62]. Then we look for poles of T matrix in the complex plane of  $\sqrt{s}$ . If pole appears in the first Riemann sheet below threshold, it is considered as bound states whereas it located in the second Riemann sheet and above the threshold of some channels is identified as resonance. This meson-baryon model dynamically generates six narrow states from PB and VB channel: two  $N^*$  resonances and four  $\Lambda^*$ resonances. As shown in Tab. I, all of these resonances are with mass around 4.3 GeV and width smaller than 100 MeV. In the Valencia approach, a static limit is assumed, which leads to neglect spin and momentum dependent terms of interaction potential. Therefore, only S-wave is considered here. The predicted resonances from PB channels have  $J^P = \frac{1}{2}$ , while from VB channels there are degenerated  $J^P = \frac{1}{2}^-$  and  $\frac{3}{2}^-$  states. Obviously, these super-heavy  $N^*$  and  $\Lambda^*$  resonances have nearly pure  $qqqc\bar{c}$  (q = u, d or s) components because they are all the qusi-bound states of anti-charmed meson-charmed baryon with negligible couplings to channels without charm.

**Table I.** Pole position  $(Z_R)$ , mass M and total width  $\Gamma$  (including the contribution from the light meson and baryon channel). The units are in MeV.

	PB channel			VB channel		
(I,S)	$Z_R$	M	Γ	$Z_R$	M	Γ
(1/2,0)	4265 – 11.6i	4261	56.9	4415 – 9.5 <i>i</i>	4412	47.3
(0,-1)	4210 - 2.9i	4209	32.4	4547 - 2.8i	4368	28.0
	4398 - 8.0i	4394	43.3	4368 - 6.4i	4544	36.6

To investigate the possible influence of the assumption of potential in the Valencia approach, Ref. [63] uses EBAC approach to re-check the prediction of baryons with hidden charm. In this

approach, the T matrix is solved from the three dimensional scattering equation which is a reasonable assumption of BS equation. It is benefit to avoid any assumption of the potential. In this calculation, the  $N^*$  and  $\Lambda^*$  resonances are also dynamically generated although the mass and width of them are slightly different.

On the other hand, by replacing  $c\bar{c}$  with  $b\bar{b}$  and using the same meson-baryon model with the Valencia approach, two  $N^*$  resonances and four  $\Lambda^*$  resonances with hidden beauty are dynamically generated. Because of the super heavy  $b\bar{b}$  pairs involved in these states, masses of them are all around 11 GeV while widths are only a few MeV. In order to study the uncertainties from the assumption of the Valencia approach, especially from the momentum dependent terms, we also used the conventional Schroedinger Equation approach to confirm the  $N^*$  with hidden beauty from  $B\Sigma_b$  channel [64]. The consistent result gives some justifications of the simple Valencia approach. Before the new observations from the LHCb collaboration [43], there were a lot of predictions about these super-heavy states with hidden charm in other meson-baryon models, with masses above  $J/\psi p$  threshold [65–67] in consistent with ours [41,42] although there were some earlier predictions with masses below  $J/\psi p$  threshold [68,69]. It shows that a series of super-heavy  $N^*$  and  $\Lambda^*$  resonances possibly exist around 4.3 GeV and 11 GeV in various meson-baryon scattering models.

Unlike above meson-baryon scattering models, penta-quark state  $|qqqq\bar{q}\rangle$  can be also consisted of the colored quark cluster [qq][qq] and  $\bar{q}$ . Ref. [70] uses three kinds of schematic interactions, the chromomagnetic interaction, the flavor-spin dependent interaction and the instanton-induced interaction, to study low-lying energy spectra of penta-quark system with  $uudc\bar{c}$  and  $udsc\bar{c}$ . The lowest penta-quark state has an S-wave orbital angular momentum and  $J^P=1/2^-$ , and they are predicted with the mass around 4.1 GeV. The interesting thing is that here the predicted lowest mass of  $udsc\bar{c}$  state is heavier than the  $uudc\bar{c}$  state, because the strange quark is heavier. However, as shown in Tab. I, the lowest  $\Lambda^*$  resonance is lighter than the  $N^*$  resonance in the meson-baryon scattering model, because the threshold of  $\bar{D}_s\Lambda_c^+$  is below that of  $\bar{D}\Sigma_c$ . The different mass order between  $N^*$  and  $\Lambda^*$  resonances can be used to distinguish these two models in the future.

### 3.2 Experiment evidence and further exploration

Just after this conference, two states  $P_c^+(4380)$  and  $P_c^+(4450)$  were claimed to be observed in the invariant mass spectrum of  $J/\psi p$  in decay reaction  $\Lambda_b \to J/\psi K^- p$  by the LHCb Collaboration [43]. Their masses are found to be  $4380 \pm 8 \pm 29$  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, respectively. The preferred  $J^P$  assignments are of opposite parity, with one state having spin  $\frac{3}{2}$  and the other  $\frac{5}{2}$ . This new observation attracts a lot of theoretical interests. There are three different views of these two new states: a) anticharmed meson-charmed baryon molecular states [71–74], b) penta-quark states consisted of colored quark cluster based on diquark models [75, 76], and c) a kinematical effect for one peak [77, 78].

Obviously, the first and the second views which both regard these two states as multi-quark states are consistent with previous Refs. [41,42,63,65–67] and Ref. [70], respectively. In order to confirm whether they are genuine physical states or just some kinematical effects, as well as to find other such heavy states with different quantum numbers, new experiments for these super-heavy states is essential. In Refs. [41,42,63,79,80], the reaction  $\gamma p \to J/\psi p$  has already been proposed to look for the  $N^*$  within hidden charm, possibly at the CEBAF-12 GeV-upgrade in Jefferson Lab. Furthermore, other possible channels  $\eta_c p$  and  $\Upsilon p$  are also suggested for searching the new  $N^*$  resonance within hidden charm and beauty, respectively. For the PANDA/FAIR, with a  $\bar{p}$  beam of 15 GeV one can get the total energy of  $\bar{p}p$  collisions arrive 5470 MeV, which allows one to observe  $N^*$  resonances in pX production up to a mass  $M_X \sim 4538$  MeV or a  $\Lambda^*$  resonances in  $Y\Lambda$  production up to a mass  $M_Y \sim 4355$  MeV. It will be a nice place to examine the existence of super-heavy  $N^*$  and  $\Lambda^*$  resonances. These super-heavy  $N^*$  and  $\Lambda^*$  could also be looked for from  $\pi p$  and Kp experiments [81,82], possibly at JPARC. And for the  $N^*$  with hidden beauty, the available center-of-mass energies of pp and ep

collisions are larger than 13 and 14 GeV, respectively, and cross sections of  $pp \to pp\Upsilon$  and  $e^-p \to e^-p\Upsilon$  should be larger than 0.1 nb. It is expected new facilities in future, such as proposed electron-ion collider [13].

## 4. Conclusions

With more and more hadronic states being discovered in experiments, the quenched quark models become too simple to explain properties of various hadrons, while the unquenched quark models are needed. Comparing to the orbital angular momentum excitation mechanism in quenched quark models, the  $q\bar{q}$  dragged out from gluon field is another important excitation mechanism for hadrons. It is necessary to go beyond the classical quenched quark model: the number of quarks in a hadron is not a constant. New experimental observations of the CB group play a key role for understanding hyperon spectrum, and new analyses of these data strongly support unquenched quark model. Furthermore, based on the transition between sss and sss $q\bar{q}$  with the NJL model and instanton-induced interaction, the new lowest  $\Omega^*$  is predicted around 1780 MeV. It is expected to be observed in the  $\psi(2S) \to \bar{\Omega}\Omega^*$  reaction at BESIII. In order to avoid the mixture between five-quark and three-quark components in baryons, we extend several models of baryons to the cases with hidden charm and beauty. Then a series of super-heavy  $N^*$  and  $\Lambda^*$  resonances with hidden charm and beauty are predicted to be around 4.3 GeV and 11 GeV from various unquenched quark models. Fortunately, two of such  $N^*$  with hidden charm might have been observed by the LHCb experiment. Confirmation from other experiments and some further detailed investigations of these new  $N^*$  resonances from both experimental and theoretical sides are essential to build up penta-quark dynamics. Searching for their partners of various quantum numbers are also crucial for understand the multi-quark dynamics.

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