The Excitement and Challenging Issues Concerning the Discovery of Heavy Pentaquark Candidates with Hidden Charm

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ABSTRACT

In this mini-review we try to understand the present status of the study of hidden heavy flavor pentaquark states. Several scenarios, namely, baryon-meson molecules, diquark/triquark states, and anomalous triangle singularity kinematic effects, are reviewed. Some challenging issues concerning the internal effective degrees of freedom of these pentaquark candidates and their manifestations in the production and decay processes are addressed.

INTRODUNTION

In early 1960's when more and more hadrons were observed in experiments, how to arrange the "particle zoo" had been a crucial motivation for a better understanding of the fundamental "strong force". The success of the quark model proposed by Gell-Mann [1] and Zweig [2] in 1964 exposed for the first time that more tiny structures of so-called "quarks (antiquarks)" held together by the strong force would account for the patterns of the particle zoo where a baryon is made of 3 quarks (qqq) while a meson is made of quark-antiquark ($q\bar{q}$).

During the past years high-statistics data from high-energy experimental facilities such as BaBar, Belle, CLEO-c, BESIII, and LHCb, have revealed strong evidence for hadrons beyond the simple quark model scenario. They either cannot be accommodated into the successful quark-model predicted spectra, or appear to have unusual production or decay modes that are different from expectations forsimple quark model structures. The most interesting and exciting ones are those for which the minimum number of constituent quarks must be more than either simple $q\bar{q}$ for a meson or qqq for a baryon. For instance, the observations of charged heavy-quarkonium-like states $Z_c(4430)$, $Z_b(10610)$ and $Z_b(10650)$ at Belle, $Z_c(3900)$ at BESIII, Belle and CLEO-c, and $Z_c(4020)$ at BESIII, have indicated that we must have missed certain pieces of information about the non-perturbative strong interaction dynamics.

In 2015 LHCb reported the observation of possible heavy pentaquark candidates $P_c(4380)$ and $P_c(4450)$ in the invariant mass spectrum of $J/\psi p$ in $\Lambda_b \to J/\psi p K^-$ [3]. Their masses (widths) are 4380 8 29 MeV(205 18 86 MeV) and 4449.8 1.7 2.5 MeV (39 5 19 MeV), respectively, and their preferred J^P are either $3/2^-$ and $5/2^+$, or $3/2^+$ and $5/2^-$, respectively, depending on the detailed experimental analysis. It revived the study of pentaquark baryons and immediately initiated many theoretical efforts to understand their nature.

One of the obvious features that make the heavy pentaquarks with hidden flavors interesting is that their masses are much higher than the conventional 3-quark N^* baryons and their widths should be much narrower than the typical widths of N^*s. For instance, for a pentaquark with hidden charm, its mass should be at least around $M_{J/\psi}+M_N \simeq 4$ GeV, and in such a mass region, any N^* state of qqq will become extremely broad and cannot be identified from background. However, if there are hidden heavy flavors involved in the quark wavefunction of such a heavy baryon, the constituent degrees of freedom may develop into more stable systems and manifest themselves as heavy narrow baryons above the conventional $qqqN^*$ states as suggested by Refs. [4,5]. There are also suggestions on searching for their production signals in experiment [6,7]. The observation of the $P_c(4380)$ and $P_c(4450)$ in the $J/\psi p$ invariant mass spectrum may shed light on such a dynamic mechanism.

Interestingly, it shows that there are still many unanswered questions following this exciting experimental result. While there have been efforts towards tackling some of those questions, it is worth addressing some of those challenging issues concerning their structures, production mechanisms, and decay modes. A review of the present status of the study of the heavy pentaquark states will be presented in Section II. Discussions on some of those challenging issues will be given in Section III.

PENTAQUARKS IN DIFFERENT SCENARIOS

Different theoretical interpretations for the structures of these two observed pentaquark candidates have been proposed in the literature. They are based on different dynamical scenarios but none of these is indisputable although they may have captured some specific features concerning the underlying dynamics.

For a system of five quarks (4 quarks plus one antiquark), quark clusterings have been a useful effective degrees of freedom for studying the structures and underlying dynamics. There are two categories to which one can assign the multiquark phenomena. One is that the five quarks are separated as two color singlet states bound by a colorless nuclear force. This is similar to the binding of a proton and a neutron by the nuclear force to form deuteron. Such states are labeled as hadronic molecules. The other one is that the quarks will cluster into either diquarks or a colored triquark ($\bar{q}\,(q'q'')$) where the effective interactions between the clusters are still colored. Namely, the pentaquark will be an overall color-singlet state. There are also non-resonance interpretations in the literature. In the following we will discuss these scenarios and try to gain some insights into such a multiquark system.

(A) Baryon-Meson Molecules

The long-range pion exchange potential plays a crucial role in the hadronic molecule scenario. It behaves differently in different spin-isospin channels which can be either attractive or repulsive. This has been recognized long ago e.g. in nucleon-nucleon scatterings. Törnqvist did the first systematic analysis of the charmed meson system and predicted the existence of a $D\bar{D}^*+c.c.$ molecular state with $I = 0$ and $J^{PC} = 1^{++}$ due to the attractive pion exchange potential in this channel [8]. The $X(3872)$ discovered by the Belle Collaboration [9] has been the best candidate that fits many aspects of this prediction[10].

If the long-range pion exchange potential is indeed the key mechanism driving the formation of hadronic molecular states, there are certain general features that one would expect: (I) The interacting hadrons should carry isospin to allow the pion to be exchanged. For instance, the $D^*\Lambda_c$ system does not allow single pion exchange to contribute to $\bar{D}^*\Lambda_c \to \bar{D}^*\Lambda_c$. Coupled channel contributions may become important here via e.g. $\bar{D}^*\Lambda_c \to \bar{D}^*\Sigma_c$. However, so far, it is not clear how reliable it is to include such an effect in the potential model calculations. (II) For two states with spin and isospin, the pion exchange potential to be attractive or repulsive will depend on the total spin and total isospin of the system. This will provide practical criteria for a bound or unbound system [11,12]. However, it is not clear what is the role played by the short-distance interactions.

Following the publication of the LHCb data [3], an immediate theoretical interpretation of $P_c(4380)$ and $P_c(4450)$ was given by Ref. [13] where the authors proposed that these two states are molecular states formed by the $\bar{D}^*\Sigma_c(2455)$ and $\bar{D}^*\Sigma_c^*(2520)$ state via the long-range pion exchange potential. Notice that both $P_c(4380)$ and $P_c(4450)$ have fixed isospin 1/2 since they decay into $J/\psi p$. The quantum number favored by Ref. [13] are $(I, J^P)=(1/2, 3/2^-)$ and $(1/2, 5/2^-)$ for $P_c(4380)$ and $P_c(4450)$, respectively. This assignment of quantum numbers is actually different from the favored ones from the experimental partial wave analysis. Taking into account the spin-isospin symmetry with the pion exchange potential, the authors of Ref. [13] predicted possible partner states with $(I, J^P)=(3/2, 1/2^-)$ and $(3/2, 1/2^-)$ for the $\bar{D}^*\Sigma_c(2455)$ and $\bar{D}^*\Sigma_c^*(2520)$ system, respectively. These two states will then decay into $\Delta(1232)\,J/\psi$ and $\Delta(1232)\,\eta_c$ due to isospin conservation.

It is interesting to note some early studies of the relevant phenomena. In Refs. [4,5] the interactions between charmed mesons and charmed baryons were investigated in the framework of a coupled channel unitary approach. In the system composed of ground state charmed baryons (e.g. Λ_c, Σ_c, Ξ_c) and charmed mesons (e.g. $\bar{D}$, $\bar{D}^*$, $\bar{D}_s$ and $\bar{D}_s^*$), several dynamically generated narrow meson-baryon resonances with hidden charm were predicted with masses above 4 GeV and widths smaller than 100 MeV. One interesting feature arising from this prediction is that the widths of those states appear to be rather narrow although plenty of phase space is allowed for their decays. The crucial reason is because only *t*-channel vector meson exchange is considered. The propagator is approximated by $g^{\mu\nu}/M_V^2$, namely, by assuming that the three-momentum and kinetic energy are much smaller than the vector meson mass. This assumption can be applied to weakly bound systems which also means that significant uncertainties may arise from such a treatment. Then, it should also be noted that in case of $\bar{D}^*\Sigma_c(\Sigma_c^*)$ interaction, long-range pion exchange is allowed and its impact on the binding condition should be investigated.

In a following work [14] the authors formulated the coupled-channel calculations for dynamically generating $P_c(4380)$ and $P_c(4450)$ via $J/\psi p$, $\bar{D}^*\Lambda_c$, $\bar{D}^*\Sigma_c$, $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c^*$. The authors showed that the $P_c(4450)$ should be dominated by the $\bar{D}^*\Sigma_c(2455)$ and $\bar{D}^*\Sigma_c^*(2520)$ configuration which is consistent with the results of Ref. [13]. However, for both of the pictures in Refs. [13] and [14], the production mechanism shown in Ref. [3] does not support the creation of the isovector states $\Sigma_c^{(*)}$ at leading order if the initial u and d quark are always combined together as an isospin-0 diquark in the transitions. It was then proposed in Ref. [14] that the $J/\psi p$ rescatterings into $\bar{D}^{(*)}\Sigma_c^{(*)}$ will give access to the production of the molecular pentaquark states. However, since the masses of the pentaquark candidates are quite far away from the $J/\psi p$ threshold, the $J/\psi p$ component in the pentaquark wavefunction should indeed be negligibly small. Thus, the configuration of $\bar{D}^{(*)}\Sigma_c^{(*)}$ generated by the $J/\psi p$ rescatterings will be further suppressed.

In Ref. [15] it was pointed out that the diquark cluster is not necessarily spatially compact. Therefore, the weak decay of $b \to c(\bar{c}s)$, which is an extremely short-distance process, will allow the $\bar{c}$ to pick up an initial light quark to form a $\bar{D}^{(*)}$ meson. Alternatively, it can equally be said that the interacting range of $b \to c(\bar{c}s)$ is much smaller than the size of the light ud diquark. Then, with an additional light quark pair created from the vacuum, a $\Sigma_c^{(*)}$ can be produced at leading order. Note that the color suppression factor of such a process (see Fig. 1 (c) of Ref. [15]) is the same as the process of $\Lambda_b \to J/\psi\Lambda^* \to J/\psi pK^-$. This mechanism will allow leading-order interactions between $\bar{D}^{(*)}$ and $\Sigma_c^{(*)}$, which may form the pentaquarks as suggested by Refs. [13,14].

In Ref. [16], noticing that the mass of the $P_c(4450)$ sits almost exactly at the threshold of $\chi_{c1}p$, the authors discussed the possibility that the $P_c(4450)$ might be a $\chi_{c1}p$ resonance that is enhanced by kinematic effects.

In order to understand the potential model results, better understandings of various potential models [13,14,17,18] and the reaction mechanisms [19] are certain to be needed.

(B) Pentaquark as an Overall Color Singlet State

The quark clustering picture is an alternative prescription for the multiquark hadrons beyond the simple quark model states. The idea of diquark correlations was proposed by Jaffe in his seminal works [20,21]. A further elaborated picture was presented in Ref. [22] following the discovery of the light pentaquark $\Theta^+(1540)$. Although the $\Theta^+(1540)$ faded away with high-statistics experiments, the property of diquark clusterings were broadly explored and initiated many theoretical investigations.

In Ref. [23], it was proposed that the pentaquark candidates $P_c(4380)$ and $P_c(4450)$ contain (cq) and (qq') diquarks associated by an anti-charm $\bar{c}$. In order to match the experimentally favored quantum number $3/2^-$ and $5/2^+$ for $P_c(4380)$ and $P_c(4450)$, respectively, the authors propose that these two states have spin structures of $P_c(3/2^-)=\{\bar{c}[cq]_{s=1}\ [q'q'']_{s=1},\ L=0\}$ and $P_c(5/2^+)=\{\bar{c}[cq]_{s=1}\ [q'q'']_{s=0},\ L=1\}$, respectively. The spin-1 diquarks are classified as the so-called "bad diquarks" by Jaffe [24] that are less favored to form stable multiquark hadrons than the "good diquarks" with spin 0 and color $\bar{3}$. This may explain why the $P_c(4380)$, if assigned by $J^P=3/2^-$, appears to be broader. For the narrow $P_c(4450)$, the orbital excitation will be compensated by the mass splitting between the spin-0 and spin-1 diquarks. Thus, its mass is less than 100 MeV heavier than that of the $P_c(4380)$. But it is not clear why its width should be much narrower than the latter.

An interesting feature arising from the diquark clusterings is that there will be certain numbers of states to be expected based on the spin and flavor symmetry. For instance, it would be curious to ask whether the "good diquarks" of $\{\bar{c}[cq]_{s=0}\ [q'q'']_{s=0},\ L=0\}$ can form stable pentaquark states or not? Whether there exist flavor partners of these pentaquark states? And what would be their mass range and decay modes? Some of those questions are explored in Refs. [25-28] while more can certainly be raised. One can see that there might have been some channels for which the experimental data have been accumulated. Thus, experimental examinations of these different theoretical scenarios should be highly recommended.

Another possible quark clustering picture was proposed in Ref. [25] where the author arranges the five quark system as a color-antitriplet diquark cu and color-triplet $\bar{c}(ud)$, which will rapidly separate before hadronization, namely, before decaying into final-state color-singlet hadrons. It was argued that the color-rearrangement in such a situation will bring suppression to the decays and lead to relatively narrow decay widths. Another analysis based on the diquark-triquark picture was presented in Ref. [29]. It should be mentioned that a similar quark clustering scenario was proposed earlier by Karliner and Lipkin to understand the light pentaquark $\Theta^+(1540)$ [30].

(C) Non-resonance interpretations

The appearance of $P_c(4380)$ and $P_c(4450)$ close to some open charm thresholds also raises questions of whether they could be produced by kinematic effects. During past years it has been recognized that special kinematic effects may generate measurable effects near threshold and some of those near-threshold enhancements may not be genuine states. Here, the special kinematic effects refer to the anomalous triangle singularity (ATS) for the three-point loop functions in the final-state interactions.

The ATS was first noticed by Landau [31] who identified that there exist several kinds of singularities for a 3-point loop function and that the location of the singularities in the complex plane of the external momentum variables can be determined by a set of Landau equations [31]. In specific kinematic regions it would allow that all the three internal lines approach their on-shell conditions simultaneously. This situation defines the ATS which corresponds to the leading singularity of the triangle diagram [32]. It should be noted that the ATS is different from the branch singularities in which only two of the internal lines are on-shell. Such singularities are actually lower-order singularities in comparison with the ATS.

In a series of recent papers [33-38], it has been shown that the ATS indeed occurs in various processes and produces visible threshold enhancement effects in the invariant mass spectrum. Such effects, although created by non-resonance kinematics, may mix with the near-threshold pole structures and complicate the threshold phenomena [35].

For the decay of $\Lambda_b \to J/\psi pK^-$, the ATS is found to contribute via intermediate processes. In Refs. [15,39], it was shown that the intermediate process $\Lambda_b \to \chi_{c1}\Lambda^*(p) \to J/\psi pK^-$ would allow the ATS condition to be fulfilled within the physical region, where the rescattering $\chi_{c1}p \to J/\psi p$ is implied. The singular threshold is located almost exactly at amass of 4.45 GeV which is the same as the mass of the narrow $P_c(4450)$.

It can also occur that the Λ_b weak decays go through the transition $\Lambda_b \to \Lambda_c^{(*)}\ \bar{D}_{sJ}^{(*)}\ (\bar{D}^{(*)}) \to J/\psi pK^-$ where $\Lambda_c^{(*)}\ \bar{D}^{(*)} \to J/\psi p$ is implied. For the exchange of D meson in the rescattering of $\Lambda_c(2595)$ and $\bar{D}_{sJ}^*$, the satisfyingof the ATS condition will create singular peaks at the threshold mass of $\Lambda_c(2595)\ \bar{D}$, which is also located at the mass of the $P_c(4450)$.

It should be noted with caution that the ATS peaks in $\Lambda_b \to J/\psi pK^-$ suffer from some model-dependent ambiguities when higher partial wave couplings are involved. For the production of the $P_c(4380)$ and $P_c(4450)$ with quantum numbers beyond the S wave meson-baryon couplings, the ATS peak will generally become less predominant. Another effect that will make the ATS peaks less significant is the widths of the intermediate states. In general, with the broad intermediate states the ATS peak will flat out. However, it was also shown by Ref. [15] that in some channels, the ATS peak can survive even with P-wave couplings and relatively broad widths for the intermediate states. In such a sense, the ATS non-resonance scenario needs further investigations.

MORE INSIGHTS INTO THE PENTAQUARK CANDIDATES

Although there has been much theoretical work providing interpretations, as mentioned in the previous section, there are also essential questions that should be addressed in a coherent way in future efforts. Some urgent ones that can be regarded as messages from the observed pentaquark candidates $P_c(4380)$ and $P_c(4450)$ are listed as follows:

- What are the effective degrees of freedom in the formation of heavy pentaquark states?

  For the diquark-diquark or diquark-triquark models such quark clustering pictures imply the existence of more pentaquark states (or in general, more multiquark states) than observed in experiment. It will be essential to understand how detailed dynamics would compensate such a situation. Namely, on the one hand, there are observations that can be possibly interpreted in the paradigm of quark clusterings, but on the other hand, the number of observed states are much less than expected.

  For the molecular scenario the hadron interactions involving the hadronic degrees of freedom will drive the dynamics for the pentaquark. A major character of such a scenario is that the hadronic molecules are expected to be close to the threshold of the constituent hadrons. Although the long-range pion exchange potential will play an important role, in many cases the short-distance interactions are also crucial for the constituent hadrons to be bound. As a result, it is hard to predict unambiguously whether hadronic states can be formed or not, and how many states will be expected. Such a situation becomes even more unclear if kinematic effects such as the ATS mechanism are involved. We will come back to this later.

- How are the heavy pentaquarks produced and what should be their dominant decay channels?

  The pentaquark production mechanisms in $\Lambda_b \to J/\psi p K^-$ should be better understood. As mentioned earlier, if the initial ud diquark behaves as a compact spectator in the decay and conserves its isospin 0 to form either $\Lambda_c^{(*)}$ or $\Lambda^{(*)}$ after the weak decay of the b quark, the interpretation of the pentaquarks based on the $\bar{D}^{(*)}\Sigma_c^{(*)}$ interactions will encounter serious problems since the $\Sigma_c^{(*)}$ states can only be created as subleading contributions. The proposed mechanism in Ref. [15] will allow the production of $\Sigma_c^{(*)}$ at leading order given that the diquark cluster is not necessarily spatially compact.

  Another interesting production mechanism was proposed in Ref. [40] where the authors argue that the heavy pentaquark production should occur via the QCD factorizable diagram where the $c\bar{c}$ is created from the intrinsic charm of the Λ_b while the weak decay will be via the charmless b decay, $b \to u(\bar{u}s)$. Such a process can be a complementary production source given that the intrinsic charm component is sizeable in the Λ_b wavefunction. But even so, it is nontrivial to describe that the highly virtual $c\bar{c}$ in the Λ_b wavefunction becomes (almost) on-shell in the final state pentaquark. Momentum transfers from the decayed b quark to the $c\bar{c}$ pair are thus needed and it is not necessary to have the gluon exchanges absorbed into the final state wavefunction.

  The decay of the pentaquarks in different scenarios may shed some light on their internal effective degrees of freedom. The narrow width of $P_c(4450)$ can be reasonably understood if it is a molecular state of $\bar{D}^{(*)}\Sigma_c^{(*)}$ since its decays into charmonium and light meson will be via the loop transitions [4,14,41]. In contrast, in the scenario of color-singlet pentaquarks, there is no obvious suppression mechanism for the color rearrangement into the final charmonium and light meson. With the large phase space, one would expect that, for instance, the $J/\psi p$ should be the dominant decay channel for the P_c states. Therefore, it should be useful to investigate the relative branching fractions of these pentaquark decays into open charm and charmonium states in various models.

  With the SU(3) flavor symmetry and even hidden $b\bar{b}$ considered, the existence of the flavor partners of the P_c states were explored in different scenarios. In Refs. [27,42-44] the heavy pentaquark partners with strangeness have been surveyed and some possible decay channels were suggested for future experimental searches.

- Where to look for more pentaquark states?

  There must be other processes which allow the production of pentaquark states and can be accessed by experimental measurement. Apart from $\Lambda_b \to J/\psi p K^-$, other production processes were also proposed for these hidden charm pentaquarks in $\Lambda_b^0 \to J/\psi p \pi^-$ [45], J/ψ photoproduction [46-48], πN scattering [49-51], and heavy ion collisions [52,53]. Proposals for the search for their partners with strangeness $S = -1$, such as $\Lambda_b \to J/\psi K^0 \Lambda$ [54], $\Lambda_b \to J/\psi \eta \Lambda$ [55], and $\Xi_b \to J/\psi K \Lambda$ [56], or with double charm [57], can also be found in the literature. The natural thinking is that if the pentaquark states do exist, there cannot be just one or two to be observed. One would expect more states with either different spin-parity, or different flavor contents. Otherwise, there must be an extreme reason behind the observed signals.

- How to distinguish a genuine pentaquark state from possible kinematic effects?

An interesting and natural feature arising from the ATS mechanism is that the threshold peaks are predictable and they only appear when the kinematic conditions are satisfied. As a consequence, it implies that such threshold peaks will disappear in processes where the ATS conditions are not fulfilled. Such a feature will provide criteria for judging whether a threshold enhancement is created by the ATS kinematic effects or by a genuine pole via final state interactions.

In Refs. [46] it was proposed to probe the structure of the pentaquarks in J/ψ photoproduction off a nucleon. Similar ideas were also presented in Refs. [47,48]. It can be seen that the J/ψ photoproduction does not allow the same ATS kinematics, as in $\Lambda_b \to J/\psi p K^-$, to be recognized. Meanwhile, it can benefit from the experimental fact that the pentaquark states are coupled to $J/\psi p$. Note that S-channel pentaquark productions via high energy photon-nucleon scatterings can implement the vector meson dominance (VMD) model for photon-J/ψ coupling. Then the strong production and decay of the pentaquarks can be consistently connected to their couplings to $J/\psi p$. Apart from a cut-off parameter introduced for the strong interaction form factor, the photoproduction of the S-channel pentaquarks will be constrained.

Recently, the new data for $\Lambda_b^0 \to J/\psi p \pi^-$ from LHCb [58] indicate further signals for the exotic pentaquark states in the $J/\psi p$ invariant mass spectrum. Interestingly, it was shown by Ref. [59] that the ATS mechanism is still located within the physical region and the ATS peak can still account for the enhancement in the spectrum. This makes the J/ψ photoproduction extremely useful for the purpose of searching for and confirming the heavy pentaquark exotics.

- Can lattice QCD provide a better insight into the pentaquark dynamics?

There are calculations of the pentaquark states in the framework of QCD sum rules [60-62] where different interpolating currents were applied. In principle, different forms of the interpolating currents can be related by the color rearrangement and Fierz transformation. Their overlap with the state will reflect, to some extent, the nature of its internal structure. However, it should be realized that since the interpolating currents are local ones, it may still occur that two different types of currents both have large overlaps with the state. In Refs. [60] and [61] the authors both find that $P_c(4380)$ and $P_c(4450)$ favor $J^P=3/2^-$ and $5/2^+$, respectively. But the constructed interpolating currents are based on different scenarios for the pentaquarks, namely anti-meson-baryon interaction current [60] and diquark-diquark-antiquark current [61,62]. This may indicate that these pentaquark states are quite deeply bound in the molecular scenario and cannot be distinguished from the diquark-diquark-antiquark picture.

Taking into account other uncertainty sources, our ultimate knowledge about the multiquark systems may have to rely on the lattice QCD (LQCD) simulations. Although it is still not possible to carry out a full calculation of the hadron spectra, physicists are making significant progresses and the development is moving forward quickly. Recent LQCD calculations for the exotic candidates $X(3872)$ and $Z_c(3900)$ have revealed interesting insights into their exotic nature.

In summary, in this short review we hope to have captured the present main progress in the study of the topic heavy pentaquark candidates $P_c(4380)$ and $P_c(4450)$. Several scenarios were reviewed, including the meson-baryon molecules, overall color-singlet five quark states, and kinematic effects due to the ATS mechanism [64]. As emphasized earlier, the experimental progress has provided important information that has prompted theoretical developments. Obviously, there have been many novel insights into the underlying dynamics based on different prescriptions and phenomenological models. We anticipate that more data from those high energy experimental facilities, such as LHCb, Belle-II, PANDA etc, would bring more interesting and surprising results. And we expect that systematic theoretical studies in the end would lead to an overall coherent picture for our understanding of exotic hadron dynamics.

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[i] We refer the readers to Ref. [63] for a soliton model prescription for the heavy pentaquark states.

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