



# Observation of pentaquark states and prospectives of further studies

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The quark model based on quark–antiquark mesons and three-quark baryons has been very successful in classifying the hadrons. However, quantum chromodynamics (QCD) does not forbid the existence of exotic hadronic states with other quark–gluon configurations, such as glueballs (with no quark), hybrids (with quarks and excited gluon), multi-quark states (with more than three quarks), and hadron molecules (bound state of two or more hadrons). It is a long history of searching for all these kinds of states; however, no solid conclusion was reached until the recent discovery of tetraquark and pentaquark states.

The first strong experimental evidence for a pentaquark state, referred to as the  $\Theta(1540)^+$ , was reported in the reaction  $\gamma n \rightarrow nK^+K^-$  in the LEPS experiment [1]. It was a candidate pentaquark state of  $uudd\bar{s}$ . However, it disappeared in a larger statistics data sample in the same experiment and was most probably not a genuine state [2]. The overwhelming studies in theory and in experiments during that period of time was well accounted in the statement that “the story of pentaquark shows how poorly we understand QCD” [3].

A charged charmonium-like state  $Z_c(3900)$  was observed by BESIII [4] and Belle [5] experiments in 2013 in  $J/\psi\pi^\pm$  system of  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  at center-of-mass energies around 4.26 GeV. Besides the  $Z_c(3900)$ , BESIII and Belle also observed a series of charged  $Z_c$  states including  $Z_c(4020)$ ,  $Z_c(4200)$ , and  $Z_c(4430)$ . These states seem to

indicate that a new class of hadrons has been observed [6]. As there are at least four quarks within these  $Z_c$  states, they have been interpreted either as tetraquark states with a pair of charm–anticharm quarks and a pair of light quarks, molecular states of two charmed mesons, or other configurations.

Very recently, LHCb experiment reported the observation of two exotic structures, denoted as  $P_c(4380)^+$  and  $P_c(4450)^+$ , in the  $J/\psi p$  system in  $\Lambda_b^0 \rightarrow J/\psi K^- p$  [7]. The  $P_c(4380)^+$  has a mass of  $(4380 \pm 8 \pm 29)$  MeV/ $c^2$  and a width of  $(205 \pm 18 \pm 86)$  MeV, while the  $P_c(4450)^+$  is much narrower with a mass of  $(4449.8 \pm 1.7 \pm 2.5)$  MeV/ $c^2$  and a width of  $(39 \pm 5 \pm 19)$  MeV. Figure 1 shows the fit to the  $J/\psi p$  invariant mass distribution and the  $P_c(4380)^+$  and  $P_c(4450)^+$  contributions. Since the valence structure of  $J/\psi p$  is  $c\bar{c}uud$ , the newly discovered particles consist of at least five quarks.

Several theoretical interpretations of these states have been developed, including a pentaquark doublet, hadronic molecules composed of an anticharm meson and a charm baryon, a  $\chi_{c1}P$  resonance for the  $P_c(4450)^+$ , and so on [8, 9].

To confirm these pentaquark states, further experimental research should be pursued with the current available and the forthcoming experimental data. There have been many suggestions on the discovery channels for these and other exotic pentaquarks, such as (1) in  $B$  decays:  $B^0 \rightarrow p\bar{p}K^0$ ,  $\bar{B}^0 \rightarrow D^0 p\bar{p}$ ; (2) in baryon decays:  $\Lambda_c^+ \rightarrow pK^0\bar{K}^0$ ,  $\Lambda_b^0 \rightarrow K^-\chi_{c1}P$ ; (3) in quarkonium decays:  $\Upsilon(nS) \rightarrow J/\psi p + X$ ,  $\chi_{cJ}P + X$ , and  $D^{(*)-}p + X$  ( $n = 1, 2, 3$ ); and (4) in  $e^+e^-$  continuum process:  $e^+e^- \rightarrow J/\psi p + X$ ,  $\chi_{cJ}P + X$ ,  $D^{(*)-}p + X$  and  $D^{(*)}A + X$ . It is clear that a systematic search for baryon–meson resonances should be pursued in various processes, where the baryon could be  $p$ ,  $\Lambda$ ,  $\Sigma$ ,  $\Xi$ ,  $\Omega$ ,  $\Sigma_c \dots$ , and the meson be  $\pi$ ,  $\eta$ ,  $\omega$ ,  $\phi$ ,  $K$ ,  $D$ ,  $J/\psi$ ,  $\chi_{cJ}$ , and so on.

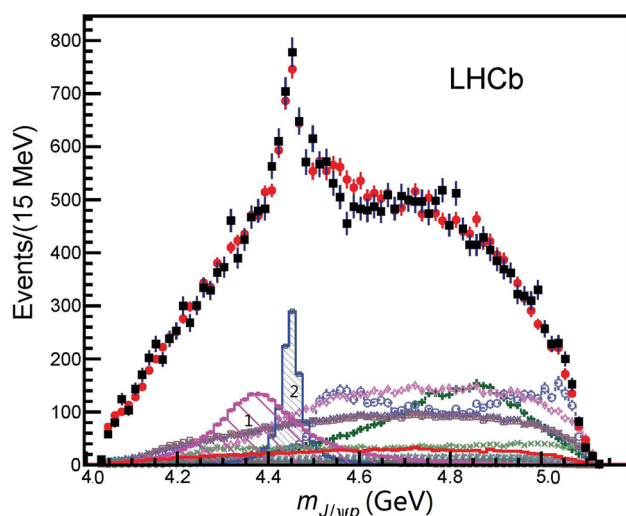
The Belle-II experiment is going to take data in 2018, the maximum energy that the Super-KEKB can reach is

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**Fig. 1** (Color online) Distribution of the  $J/\psi p$  invariant mass and the fit with two  $P_c^+$  states [7]. The hatched histogram (range 1) is the  $P_c(4380)^+$ , and the hatched histogram (range 2) is the  $P_c(4450)^+$  signal

11.24 GeV, which is just above the  $A_b$ -pair mass threshold. The  $P_c(4380)^+$  and  $P_c(4450)^+$  can be cross-checked in the same  $A_b$  decays if the production cross section of  $A_b$  is large enough.

It is worth pointing out that the tetraquark and pentaquark candidates mentioned above have a pair of charm–anticharm quarks which may annihilate. Observations of states such as  $T_{cc}^+(cc\bar{u})$  or  $\Theta_c^0(uudd\bar{c})$  or  $P_{cc}^0(ccd\bar{u})$  or similar serve as better evidences for multiquark states.

In summary, with the observation of the candidate tetraquark and pentaquark states, a new hadron spectroscopy is being revealed. Further studies along this line may strengthen our understanding of how strong interaction works at low energy and thus a better understanding of the matters around us.

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