Science Bulletin 64 (2019) 1119–1121

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

News & Views

# The pentaquarks observed by the LHCb experiment

Liming Zhang [a,*], Tomasz Skwarnicki [b], Yuanning Gao [c]

[a] Center for High Energy Physics, Tsinghua University, Beijing 100084, China
[b] Syracuse University, Syracuse, NY 13244, USA
[c] School of Physics, Peking University, Beijing 100871, China

In 1964, Murray Gell-Mann [1], the Nobel Prize winner in Physics, and George Zweig [2] separately proposed the quark model. The model revealed for the first time that a class of particles, baryons including protons and neutrons, were not elementary, instead were formed by three quarks ($qqq$), and another class, mesons, were made of quark-antiquark pairs ($q\bar{q}$). The quark model can successfully describe all the baryons and mesons (collectively referred to as hadrons) observed in the last century, thereby helps to explain how the strong force binds the quarks to form a particle. The possible existence of exotic hadrons, such as baryon with a pair of quark-antiquark added to form a five-quark particle, called pentaquark, was also suggested in their quark-model papers.

In the light quark sector ($q = u$, $d$, or $s$), unusual properties of some baryons, such as $N(1535)$ and $\Lambda(1405)$, were suggested to be due to presence of $qqqq\bar{q}$ components. However, such pentaquark components could not be clearly distinguished from the normal three-quark baryons, since the antiquark and one of the other quarks were of the same type, i.e. have the same "flavour", thus canceling each other out. For that reason, early pentaquark searches looked for particles where the antiquark flavour did not cancel. In early 2000s, several experiments reported observations of $\Theta^+$, coincided with a pentaquark state predicted with a mass of 1.53 GeV by Diakonov et al. [3], consisting of $uudd\bar{s}$ quarks. However an order of magnitude larger data showed that the peak was just a fluctuation. A detailed historical review can be found in Ref. [4].

The search for pentaquark states has been performed by many experiments in the last 50 years with an example mentioned above. Only the LHCb experiment has given a conclusive result. In 2015, the LHCb experiment reported an observation of $J/\psi\ p$ resonant structures [5,6], consistent with pentaquark with minimal quark content of $uudc\bar{c}$, produced in decays of $\Lambda_b^0 \to J/\psi pK^-$ (inclusion of charge-conjugate processes is implied throughout). Even though the "charm" flavour cancels in such combination, the presence of the $c\bar{c}$ inside the resonating particle is disclosed by the $J/\psi$ (a $c\bar{c}$ state) among the decay products, as the heavy $c\bar{c}$ pair cannot be easily created in the decay process. The data showed a prominent $J/\psi p$ peak structure at about 4,450 MeV, dubbed $P_c(4450)^+$, with the mass of $4449.8 \pm 1.7 \pm 2.5$ MeV, and the width of $39 \pm 5 \pm 19$ MeV, measured by a full six-dimensional amplitude analysis. Even though not apparent from the $J/\psi p$ mass spectrum, a second broad $J/\psi p$ state $P_c(4380)^+$, with the mass of $4380 \pm 8 \pm 29$ MeV and the width of $205 \pm 18 \pm 86$ MeV was needed by the amplitude fit to obtain a good description of the data. Whenever two uncertainties are quoted, the first one is statistical and the second one is systematic.

Recently, a refined picture was presented by the LHCb collaboration [7] with nine times larger $\Lambda_b^0$ sample than that used in the initial pentaquark discovery. Compared to the 2015 analysis, the new sample includes the additional data collected by LHCb during 2015–2018 time period. The selected $\Lambda_b^0$ yield is 246,000. Other than the additional collection time, and increased proton-proton collision energy in the second LHC run, the large yield is achieved thanks to improvements in the data selection, which returns a factor of two increase while maintaining the same background fraction.

With such large statistics, the peak structure at about 4,450 MeV is confirmed, but revealed to be a composition of two separate pentaquark states, $P_c(4440)^+$ and $P_c(4457)^+$ with nearly identical masses. A new narrow peak $P_c(4312)^+$ is also uncovered at the lower mass [7], which intensity is too small to have been detected in the smaller data set.

The new data are analysed with a simplified approach sensitive only to narrow $J/\psi p$ structures. When applying the same six-dimensional amplitude model to the new sample as in the 2015 publication, the broad $P_c(4380)^+$ state is also needed. However this study should be regarded only as a data consistency cross-check, since the 2015 amplitude model did not include the narrow $J/\psi p$ structures. Work on the improved six-dimensional amplitude model is in progress.

Since the newly observed structures are all narrow, simulation studies of pseudo-experiments prove that their masses and widths can be robustly determined by the simplified analysis, in which one-dimensional $J/\psi p$ mass ($m_{J/\psi p}$) distribution is fit with three resonant shapes and a high-order polynomial to describe any other contributions (the $\Lambda^* \to pK^-$ reflections, possible broad $P_c^+$ components and the non-$\Lambda_b^0$ backgrounds). Several $m_{J/\psi p}$ distributions with different treatment of the $\Lambda_b^0$ candidates are used. To suppress the $\Lambda^*$ reflections, a novel method is used, in which the $\Lambda_b^0$

* Corresponding author.
E-mail address: liming_zhang@tsinghua.edu.cn (L. Zhang).

https://doi.org/10.1016/j.scib.2019.06.019

candidates are weighted according to the ratio of approximate pentaquark selection efficiency and the expected statistical errors. Fig. 1 shows the fit with such event weighting procedure, which returns the best statistical sensitivity to the narrow $J/\psi p$ structures. The fit to unweighted sample, or the $\Lambda^*$ reflections suppressed by a simple $pK^-$ mass cut, are included among the systematical uncertainties. The resulting masses, widths and relative production rates ($R$) are given in Table 1. The widths of these states are quite narrow, and are comparable to the experimental mass resolution. The significance of the $P_c(4312)^+$ state is more than 7.3$\sigma$. The significance of the two-peak versus one-peak hypothesis for the 4,450 MeV structure is over 5.4$\sigma$. Therefore, the $P_c(4450)^+$ state should be considered obsolete and replaced by the $P_c(4440)^+$ and $P_c(4457)^+$ states. This, and the observation of the $P_c(4312)^+$ state, undermine the 2015 amplitude model, thus indirectly weaken the evidence for the $P_c(4380)^+$ state, but do not contradict its existence, since the present one-dimensional analysis is not sensitive to wide $P_c^+$ states.

The observed $P_c(4312)^+$ state is just 5 MeV below the $\Sigma_c^+\bar{D}^0$ mass threshold, while the $P_c(4457)^+$ is just 2 MeV below the $\Sigma_c^+\bar{D}^{*0}$ threshold. This coincidence with the two related thresholds, as well as the very narrow widths of the states favour the loosely-bound ("molecular") pentaquark model, in which the meson and baryon are bounded by a residual strong force similar to the one binding proton and neutron to form a deuteron. The third narrow $P_c(4440)^+$ peak, about 20 MeV below the $\Sigma_c^+\bar{D}^{*0}$ threshold, can also be explained naturally by this model with a different spin of the $\Sigma_c^+\bar{D}^{*0}$ combination. Several papers have predicted these states before the initial observation of the LHCb experiment (e.g. see Refs. [8–10]). If the model is true, four more partner states near the $\Sigma_c^{*+}\bar{D}^{(*)0}$ thresholds are also expected [11]. If the mass peak is very close to threshold, the state might be a virtual rather than a bound state of baryon-meson [12].

However the other explanations are not firmly ruled out. For example, Ref. [13] interpreted these new narrow $J/\psi p$ peaks as

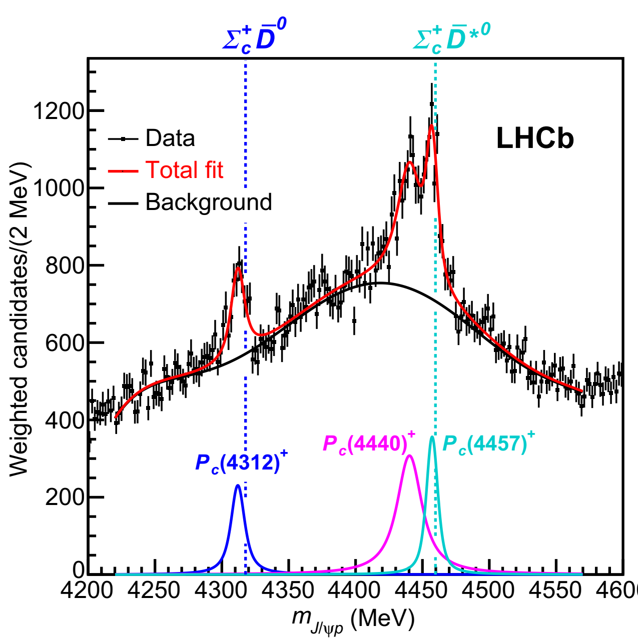


**Fig. 1.** (Color online) Distribution of $m_{J/\psi p}$ for the weighted $\Lambda_b^0 \to J/\psi pK^-$ candidates from Ref. [7] with one-dimension fit of three narrow resonances and polynomial function superimposed. A narrow peak is observed near 4,312 MeV. The structure at 4,450 MeV is now resolved into two narrow peaks at 4,440 and 4,457 MeV. The relevant charmed meson-baryon thresholds are indicated.

**Table 1**
Summary of $P_c^+$ properties.

| State | $M$ (MeV) | $\Gamma$ (MeV) (95% CL) | $R$ (%) |
|---|---|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+3.7}_{-4.5}$ (<27) | $0.30 \pm 0.07^{+0.34}_{-0.09}$ |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 4.9^{+8.7}_{-10.1}$ (<49) | $1.11 \pm 0.33^{+0.22}_{-0.10}$ |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+5.7}_{-1.9}$ (<20) | $0.53 \pm 0.16^{+0.15}_{-0.13}$ |

tightly bound pentaqaurks with diquark model. This model now faces new challenges: why these states coincide with the molecular mass thresholds and why they are so narrow. The spin-parity measurement from the amplitude analysis will be very important to distinguish these models, since the tightly bound model predicts the states $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ to be $J^P = 3/2^-$, $3/2^+$ and $5/2^+$ respectively [13], while the molecular model predicts them to be $1/2^-$, $1/2^-$ and $3/2^-$, or $1/2^-$, $3/2^-$ and $1/2^-$, respectively [11]. The new LHCb paper [7] also demonstrated that the triangle diagram processes [14–16] cannot account for $P_c(4312)^+$ and $P_c(4440)^+$.

If the $P_c(4312)^+$ is a molecular state, its existence points to the importance of vector meson ($\rho$, $\omega$) exchanges in binding the charmed baryon and meson, since a pion cannot be exchanged in the $\Sigma_c^+\bar{D}^0$ system. This may also imply that $D\bar{D}$ or $B\bar{B}$ can form bound states [17], calling for improved experimental searches.

In summary, with the nine-fold increases in the number of analysed $\Lambda_b^0 \to J/\psi pK^-$ decays, the LHCb experiment surprised us again. The $P_c(4450)^+$ peak structure in $J/\psi p$ mass spectrum is confirmed, but is resolved into two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$. In addition, a new narrow state $P_c(4312)^+$ is also observed with a significance of 7.3$\sigma$. The experimental information shed more light onto the nature of these observed narrow pentaquark states. The fact that they are very close to the $\Sigma_c^+\bar{D}^{(*)0}$ mass thresholds, suggests that these thresholds play an important role in the dynamics of these states. To further decipher their nature, the spin-parity measurement will be essential.

## Conflict of interest

The authors declare that they have no conflict of interest.

## Acknowledgments

This work was supported by Ministry of Science and Technology of the People's Republic of China (2017YFA0402103) and the National Natural Science Foundation of China (11775122). This work was also supported by the National Science Foundation (USA) Award Number 1803004.

## References

[1] Gell-Mann M. A schematic model of baryons and mesons. Phys Lett 1964;8:214.
[2] Zweig G. An SU3 model for strong interaction symmetry and its breaking, CERN-TH-401; 1964.
[3] Diakonov D, Petrov V, Polyakov MV. Exotic anti-decuplet of baryons: prediction from chiral solitons. Z Phys A 1997;359:305.
[4] Hicks KH. On the conundrum of the pentaquark. Eur Phys J H 2012;37:1.
[5] Aaij R, Adeva B, Adinolfi M, et al. Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$ decays. Phys Rev Lett 2015;115:072001.
[6] Aaij R, Adeva B, Adinolfi M, et al. Amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays. Phys Rev D 2016;95:012002.
[7] Aaij R, Beteta CA, Adeva B, et al. Observation of a narrow $P_c(4312)^+$ state and two-peak structure of the $P_c(4450)^+$ in $\Lambda_b^0 \to J/\psi pK^-$ decays. Phys Rev Lett 2019;122:222001.
[8] Wang WL, Huang F, Zhang ZY, et al. $\Sigma_c\bar{D}$ and $\Lambda_c^+\bar{D}$ states in a chiral quark model. Phys Rev C 2011;84:015203.
[9] Yang ZC, Sun ZF, He J, et al. Possible hidden-charm molecular baryons composed of anti-charmed meson and charmed baryon. Chin Phys C 2012;36:222.

[10] Wu JJ, Lee TSH, Zou BS. Nucleon resonances with hidden charm in coupled-channel models. Phys Rev C 2012;85:044002.
[11] Liu MZ, Pan YW, Peng FZ, et al. Emergence of a complete heavy-quark spin symmetry multiplet: seven molecular pentaquarks in light of the latest LHCb analysis. arXiv:1903.11560, 2019.
[12] Fernandez-Ramirez C, Pilloni A, Albaladejo M, et al. Interpretation of the LHCb $P_c(4312)^+$ signal. arXiv:1904.10021, 2019.
[13] Ali A, Parkhomenko AY. Interpretation of the narrow $J/\psi p$ peaks in $\Lambda_b \to J/\psi pK^-$ decay in the compact diquark model. Phys Lett B 2019;793:365–71.
[14] Guo FK, Meißner UG, Wang W, et al. How to reveal the exotic nature of the $P_c(4450)$. Phys Rev D 2015;92:071502.
[15] Liu XH, Wang Q, Zhao Q. Understanding the newly observed heavy pentaquark candidates. Phys Lett B 2016;757:231–6.
[16] Mikhasenko M. A triangle singularity and the LHCb pentaquarks. arXiv:1507.06552, 2015.
[17] Voloshin MB, Deciphering the XYZ states. In: 17th Conference on Flavor Physics and CP Violation (FPCP 2019) Victoria, BC, Canada, May 6-10, 2019, arXiv:1905.13156.

Liming Zhang received his Ph.D. degree from the School of Physical Sciences, University of Science and Technology of China. He is an associate professor at the Department of Engineering Physics and Center for High Energy Physics, Tsinghua University in China. His research focuses on experimental particle physics, especially CP Violation and hadron spectroscopy.