

Search for doubly-charmed baryons and study of charmed-strange baryon states at Belle

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We present the studies of charmed baryons at the Belle experiment. We search for the doubly charmed baryon Ξ_{cc}^+ in the $\Lambda_c^+ K^- \pi^+$ and $\Xi_c^0 \pi^+$ final states, and do not find any significant signals. We search for $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ in the $\Lambda_c^+ K^- \pi^+$ final state with intermediate $\Sigma_c(2455)^{++}$ or $\Sigma_c(2520)^{++}$ resonances. We observe a significant peak corresponding to the $\Xi_c(3055)^+$ while no signature of the $\Xi_c(3123)^+$ is seen. We observe $\Xi_c(3055)^{+/0}$ and $\Xi_c(3080)^{+/0}$ decays into $\Lambda D^{+/0}$ for the first time. This is also the first observation of the $\Xi_c(3055)^0$. We measure the width of the $\Xi_c(2645)^+$. It is 2.6 ± 0.2 (stat) ± 0.4 (syst) MeV/ c^2 , which is the first significant measurement.

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1. Introduction

A Charmed baryon is a good laboratory for the understanding of the low energy QCD. Because the mass of the charm quark is significantly larger than its momentum inside the hadron, we can study the static potential between quarks from the doubly charmed baryons. Also, the mass of the charm quark is much heavier than u,d,s quarks and this yields small spin-spin interaction. Therefore, we expect in the singly charmed baryon, light quarks form a di-quark. In recent years, there has been much progress in the spectroscopy of the charmed baryons driven mainly by Belle and BaBar experiments. All the singly charmed baryon ground states predicted by constituent quark model have been discovered and a number of excited states has been also discovered. However, there are still many things to be revealed in this field. There is no established doubly charmed baryon state. There are still many excited states whose experimental evidence is not strong enough to be firmly established.

In this paper, we report the studies of charmed baryons using a data sample with an integrated luminosity of 980 fb^{-1} collected with the Belle detector [1] at the KEKB asymmetric-energy e^+e^- collider [2].

2. Search for doubly charmed baryon

We search for the doubly charmed baryon Ξ_{cc}^+ in the $\Lambda_c^+ K^- \pi^+$ and $\Xi_c^0 \pi^+$ final states. The Λ_c^+ candidate is reconstructed via the decay to $pK^- \pi^+$ and pK_S^0 [3]. Ξ_c^0 candidate is reconstructed via the decay into $\Xi^- \pi^+$, $\Lambda K^- \pi^+$ and $pK^- K^- \pi^+$. In order to reduce the combinatorial background, the scaled momentum $x_p = p^*/\sqrt{s/4 - m^2}$, where p^* is the CM momentum of a Ξ_c^* candidate, s is CM energy squared and m is mass of the Ξ_c^* candidate, is required to be greater than 0.5 for $\Lambda_c^+ K^- \pi^+$ final state and 0.45 for $\Xi_c^0 \pi^+$ final state.

Figure 1 (a) shows the $M(\Lambda_c^+ K^- \pi^+)$ distribution with all the selection criteria applied. We evaluate the statistical significance of the Ξ_{cc}^+ from the formula $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L})}$, where \mathcal{L}_0 is the likelihood for the un-binned extended maximum likelihood fit without the signal component and \mathcal{L} is the likelihood for the fit with the signal component included. The statistical significance is lower than 3σ in the mass range of 3.2-4.0 GeV/c^2 . Figure 1 (b) shows the 95% confidence level (C.L.) upper limit for the product of the cross section and branching fraction to the $\Lambda_c^+ K^- \pi^+$ state for the Ξ_{cc}^+ produced with the $0.5 < x_p < 1.0$ condition,

$$\sigma_{\mathcal{B}} \equiv \sigma(e^+e^- \rightarrow \Xi_{cc}^+ X) \times \mathcal{B}(\Xi_{cc}^{+(+)} \rightarrow \Lambda_c^+ K^- \pi^+)$$

as a function of the mass. They are 4.1–25.0 fb. Figure 2 (a)-(c) show the $M(\Xi_c^0 \pi^+)$ distribution for each decay mode of the Ξ_c^0 . We perform simultaneous fit for each Ξ_c^0 decay mode with fixing the relative signal yield determined from $\Xi_c(2645)^+ \rightarrow \Xi_c^0 \pi^+$. The statistical significance for the mass around 3.553 GeV/c^2 is found to be 3.2σ . Because we scan a wide mass range, we perform a pseudo-experiment test to evaluate the probability of observing a peak with statistical significance higher than 3.2σ . The probability to observe a peak with a significance higher than 3.2σ in one pseudo-experiment is 26%. Therefore, the local statistical significance is 3.2σ is not high enough to claim it as an evidence of the Ξ_{cc}^+ . Figure 2 (d) shows the 95% C.L. upper limit for the product

of the cross section and branching fractions for the Ξ_{cc} produced with $0.45 < x_p < 1.0$ condition,

$$\begin{aligned} \sigma_{\mathcal{B}} \equiv & \sigma(e^+e^- \rightarrow \Xi_{cc}^+ X) \times \mathcal{B}(\Xi_{cc}^{+(+)} \rightarrow \Xi_c^0 \pi^+) \\ & \times \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) \end{aligned}$$

They are 0.076–0.35 fb depending on the mass.

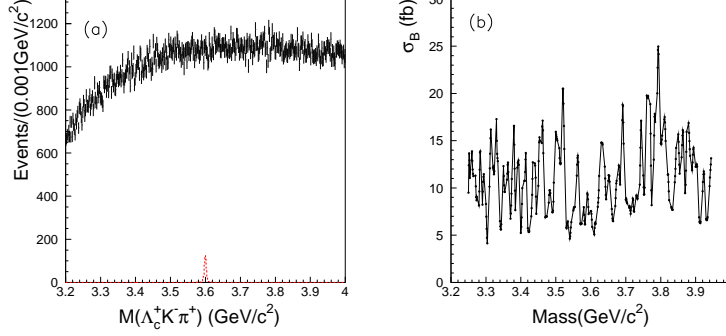


Figure 1: (a) $M(\Lambda_c^+ K^- \pi^+)$ distribution. Vertical error bars are from data and The dashed histograms are from a MC sample with a mass of $M(\Xi_{cc}^+) 3.60 \text{ GeV}/c^2$ and a production cross section $\sigma(e^+e^- \rightarrow \Xi_{cc}^{+(+)} X)$ of 500 fb and $\mathcal{B}(\Xi_{cc}^{+(+)} \rightarrow \Lambda_c^+ K^- \pi^+ (\pi^+))$ of 5%. (b) 95% C.L. upper limit of $\sigma_{\mathcal{B}}$ as a function of the mass with a $1 \text{ MeV}/c^2$ step for Ξ_{cc}^+

3. Study of the excited Ξ_c states in $\Lambda_c^+ K^- \pi^+$ final state

The Belle collaboration reported evidence of two excited states, $\Xi_c(2980)$ and $\Xi_c(3080)$, in the $\Lambda_c^+ K^- \pi^+$ and $\Lambda_c^+ K_S^0 \pi^-$ final states [4]. These states were confirmed by BaBar collaboration later [5]. In the same paper, BaBar also claimed evidence of two resonances, $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$, through intermediate $\Sigma_c(2455)^{++} K^-$ and $\Sigma_c(2520)^{++} K^-$ final states. The existence of the $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ are reported only by BaBar collaboration and an independent search by another experiment is necessary. In this study, we require the $x_p > 0.7$. Figure 3 (a) shows the The $M(\Lambda_c^+ K^- \pi^+)$ distribution with $\Sigma_c(2455)^{++}$ selection. We can see clear peak corresponding to the $\Xi_c(3055)^+$. The statistical significance of the $\Xi_c(3055)^+$ is 6.6σ . The mass is measured to be 3058.1 ± 1.0 (stat) ± 2.1 (sys) MeV/c^2 and width is measured to be 9.7 ± 3.4 (stat) ± 3.3 (sys) MeV/c^2 , which are consistent with previous measurements. Figure 3 (b) shows the The $M(\Lambda_c^+ K^- \pi^+)$ distribution with $\Sigma_c(2520)^{++}$ selection. We can not see any peaking structure corresponding to $\Xi_c(3123)^+$. The 95% C.L. upper limit for the product of the cross section and branching fraction of Λ_c^+ produced with $x_p > 0.7$ condition,

$$\sigma_{\mathcal{B}\Lambda_c^+} \equiv \sigma(e^+e^- \rightarrow \Xi_c(3123)^+ X) \times \mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)$$

is obtained to be 0.34 fb, which is much smaller than that one quoted in Ref. [5] ($1.6 \pm 0.6 \pm 0.2$ fb).

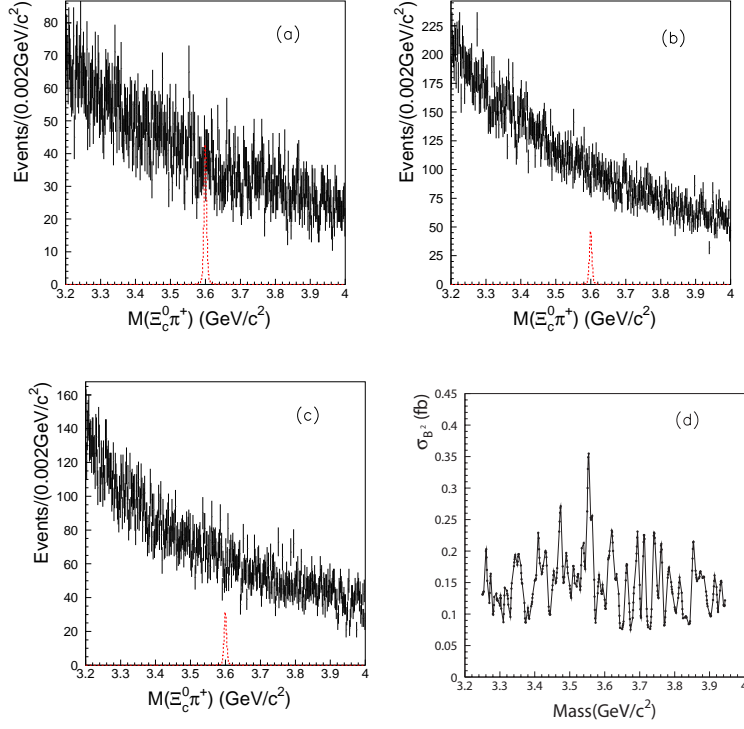


Figure 2: (a)-(c): $M(\Xi_c^0 \pi^+)$ distribution in the Ξ_{cc}^+ search region for $\Xi_c^0 \rightarrow$ (a) $\Xi^- \pi^+$, (b) $\Lambda K^- \pi^+$, (c) $p K^- \pi^+$. The vertical error bars are from data. The dashed histograms are from a MC sample with a mass of $M(\Xi_{cc}^+)$ 3.60 GeV/c^2 and a production cross section $\sigma(e^+e^- \rightarrow \Xi_{cc}^+ X)$ of 500 fb and $\mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ (\pi^+))$ and $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ of 5%. (d): 95% C.L. upper limit of the $\sigma_{\mathcal{B}^2}$ for Ξ_{cc}^+ as a function of the mass with a 1 MeV/c^2 step.

4. Study of the excited Ξ_c states in ΛD^{+0} final state

Currently, all the excited Ξ_c are found in the decay mode comprising a charmed baryon and light mesons, for example $\Lambda_c^+ K^- \pi^+$ or $\Xi_c^0 \pi^+$. It is very interesting to search for the decay mode comprising a light baryon and a charmed meson. We search for excited Ξ_c states in the ΛD^{+0} final states. The results of this section are preliminary. Λ is reconstructed via the decay into $p \pi^-$. D^+ is reconstructed via the decay into $K^- \pi^+ \pi^+$. D^0 is reconstructed via the decay into $K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$ and $K^- \pi^+ \pi^0$. Figure 4 shows the $M(\Lambda D^+)$ and $M(\Lambda D^0)$ distributions. We can see peaks corresponding to $\Xi_c(3055)^{+0}$ and $\Xi_c(3080)^{+0}$. The statistical significances are obtained to be 11.9 (4.7) σ for $\Xi_c(3055)^+$ ($\Xi_c(3080)^+$) and 7.6 (2.6) σ for the $\Xi_c(3055)^0$ ($\Xi_c(3080)^0$). This is the first observation of the $\Xi_c(3055)^0$. The mass of the $\Xi_c(3055)^0$ is obtained to be 3059.7 ± 0.6 (stat) ± 0.5 (syst) MeV/c^2 and width is 7.4 ± 1.9 (stat) ± 3.4 (sys) MeV/c^2 .

5. Measurement of the width of $\Xi_c(2645)^+$

Currently, no significant measurement for the width of $\Xi_c(2645)^+$ exists. Only the upper limit of 3.1 MeV/c^2 is given [6]. Figure 5 shows the $M(\Xi_c^0 \pi^+)$ distributions for each decay mode of Ξ_c^0 .

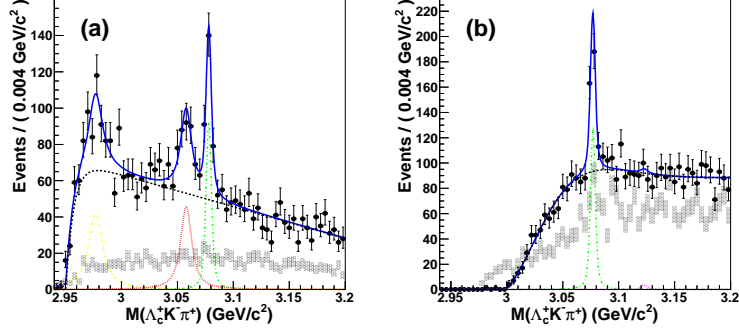


Figure 3: (a) The $M(\Lambda_c^+ K^- \pi^+)$ distribution with $\Sigma_c(2455)^{++}$ selection. The dots with error bars show the distribution for the $\Sigma_c(2455)^{++}$ selected whereas the rectangles show the distribution for the $\Sigma_c(2455)^{++}$ sideband region. Blue line shows the fit result. Black, yellow, red, and green lines show the contributions from the background, $\Xi_c(2980)^+$, $\Xi_c(3055)^+$, and $\Xi_c(3080)^+$, respectively. (b) The $M(\Lambda_c^+ K^- \pi^+)$ distribution with $\Sigma_c(2520)^{++}$ selection. The dots with error bars show the distribution for $\Sigma_c(2520)^{++}$ selected region whereas the rectangles show the distribution for the $\Sigma_c(2520)^{++}$ sideband region. Blue line shows the fit result. Black, green, and purple lines show the contributions from the background, $\Xi_c(3080)^+$, and $\Xi_c(3123)^+$, respectively.

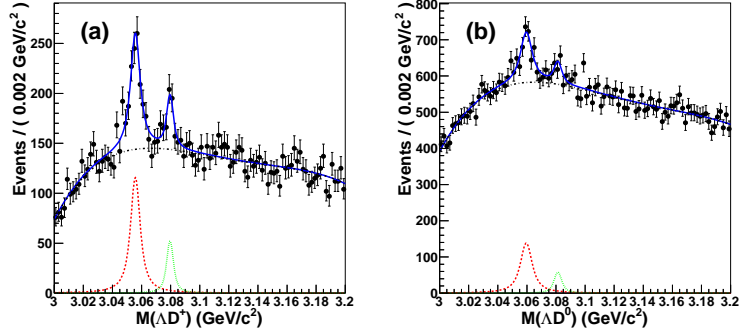


Figure 4: (a): $M(D^+ \Lambda)$ distribution. (b): $M(D^0 \Lambda)$ distribution. Blue line shows the fitting result. Black, red, and green lines show the background, $\Xi_c(3055)^{+/0}$, and $\Xi_c(3080)^{+/0}$ components, respectively.

We can see clear peaks corresponding to $\Xi_c(2645)^+$. The bump around $2.68 \text{ GeV}/c^2$ originates from the process $\Xi_c(2790)^+ \rightarrow \Xi_c^0 \pi^+ \rightarrow \Xi_c^0 \gamma \pi^+$ with the γ missing in the reconstruction. We perform simultaneous un-binned extended maximum likelihood fit with fixing mass and width of the $\Xi_c(2645)^+$. The width of the $\Xi_c(2645)^+$ is obtained to be $2.6 \pm 0.2 \text{ (stat)} \pm 0.4 \text{ (sys)} \text{ MeV}/c^2$.

6. Summary

We report the study of charmed baryons at the Belle experiment. We do not find doubly charmed baryon Ξ_{cc}^+ in the $\Lambda_c^+ K^- \pi^+$ $\Xi_c^0 \pi^+$ decay modes and put stringent upper limit on the product of the cross section and branching fractions. We confirm the existence of the $\Xi_c(3055)^+$ while we do not find significant signal of the $\Xi_c(3123)^+$ which was previously reported by BaBar

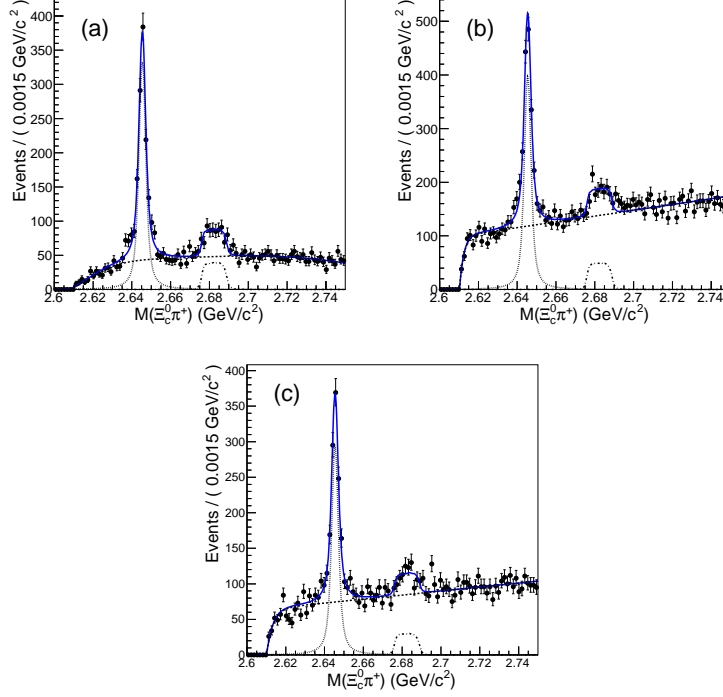


Figure 5: $M(\Xi_c^0 \pi^+)$ distributions below the Ξ_{cc} search region for (a) $\Xi_c^0 \rightarrow \Xi^- \pi^+$, (b) $\Xi_c^0 \rightarrow \Lambda K^- \pi^+$, (c) $\Xi_c^0 \rightarrow p K^- K^- \pi^+$. The solid lines show the fit result. The dashed, dotted, and dash-dotted lines show the contributions from background, $\Xi_c(2645)^+$, and $\Xi_c(2790)^+$, respectively.

in the $\Lambda_c^+ K^- \pi^+$ final state. We find the decay of $\Xi_c(3055)^{+0}$ and $\Xi_c(3080)^{+0}$ into the ΛD^{+0} final state. Especially, this is the first observation of the $\Xi_c(3055)^0$. We perform the first significant measurement for the width of the $\Xi_c(2645)^+$.

References

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