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Study of charmed strange baryons at Belle

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We report results of a study of charmed strange baryons. The analysis is performed using a 980 fb^{-1} data sample collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We search for two excited charmed strange baryons, $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ with $\Lambda_c^+K^-\pi^+$ final states through intermediate $\Sigma_c^{++}(2455)$ or $\Sigma_c^{++}(2520)$ resonances. The $\Xi_c(3055)^+$ signal is observed with a significance of 6.6 standard deviations including systematic uncertainty, while no signature of the $\Xi_c(3123)^+$ is seen. We also study $\Lambda D^{+(0)}$ final state. We observe decays of $\Xi_c(3055)^{+(0)}$ and $\Xi_c(3080)^+$ into $\Lambda D^{+(0)}$. This is the first observation of the $\Xi_c(3055)^0$.

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1. Introduction

In recent years, there has been much progress in the experimental study of the charmed baryon spectroscopy mainly by Belle and BaBar experiments. In the charmed strange baryon sector, a number of excited states (Ξ_c^*) has been observed. 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 [1]. These states are confirmed by BaBar later [2]. 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. Independent search of these two states is necessary to confirm the existences. Among a number of possible decay modes of the charmed strange baryons, the $\Lambda D^{+(0)}$ mode is not studied well.

In this paper, we report the studies of charmed strange baryons in the $\Lambda_c^+ K^- \pi^+$ and $\Lambda D^{+(0)}$ final states using a data sample with an integrated luminosity of 980 fb^{-1} collected with the Belle detector [3] at the KEKB asymmetric-energy e^+e^- collider [4]. All the results are preliminary.

2. Event selection

The Λ_c^+ candidates are reconstructed via its decay to $pK^-\pi^+$ and pK_S^0 [5]. The D^+ candidates are reconstructed via its decay to $K^-\pi^+\pi^+$. The D^0 candidates are reconstructed via its decays to $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$. The charged proton, kaon, and pion are required to have a point of closest approach to the interaction point that is within 0.2 cm in the transverse (r-ϕ) direction and within 2 cm along the z-axis. (The z-axis is opposite the positron beam direction.) For each track, the likelihood values $\mathscr{L}_p$, $\mathscr{L}_K$, and $\mathscr{L}_\pi$ are provided for the assumption of proton, kaon and pion, respectively. The likelihood ratio is defined as $\mathscr{L}(i:j) = \mathscr{L}_i/(\mathscr{L}_i + \mathscr{L}_j)$ and a track is identified as a proton if the likelihood ratios $\mathscr{L}(p:\pi)$ and $\mathscr{L}(p:K)$ are greater than 0.6. A track is identified as a kaon if the likelihood ratios $\mathscr{L}(K:\pi)$ and $\mathscr{L}(K:p)$ are greater than 0.6. A track is identified as a pion if the likelihood ratios $\mathscr{L}(\pi:K)$ and $\mathscr{L}(\pi:p)$ are greater than 0.6. In addition, electron ($\mathscr{L}_e$) likelihood is provided. A track with an electron likelihood greater than 0.95 is rejected. The efficiencies of hadron identification are about 90% for pions and kaons and 93% for protons. The π^0 candidates are selected from pair of photons whose invariant mass ($M_{\gamma\gamma}$) satisfies $120 < M_{\gamma\gamma} < 150$ MeV/c^2. The energy of each photon is required to be greater than 50 MeV/c^2 and the energy of the π^0 candidate is required to be greater than 500 MeV/c^2. The Λ candidates are selected based on their decay vertex information [6] and invariant mass of a Λ candidate is required to be within 3 MeV/c^2 of the nominal Λ mass, which corresponds to approximately 3σ of the mass resolution. The K_S^0 candidate is reconstructed from its decay into $\pi^+\pi^-$. The vertex of the two pions for the K_S^0 is required to be displaced from the interaction point (IP) in the direction of the pion pair momentum [7]. A pair of oppositely charged pions that have an invariant mass within 8 MeV/c^2 of the nominal K_S^0 mass, which corresponds to approximately 3.5σ of the mass resolution, is selected. The Λ_c^+ ($D^{+(0)}$) candidates are selected by requiring invariant mass of the daughter particles to be within 1.5 (2.0)σ of the nominal mass. The χ^2 value of the common vertex fit of the Λ_c^+ or $D^{(+)0}$ is required to be less than 50. For the remaining candidate, a mass constraint fit to the Λ_c^+ or $D^{(+)0}$ mass is performed to improve the momentum resolution. 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 and s is CM energy squared and m is mass of the Ξ_c^* candidate, is required to be greater than 0.7.

3. Results

3.1 Results for $\Lambda_c^+ K^- \pi^+$ final state

We select the $\Sigma_c(2455)^{++}$ ($\Sigma_c(2520)^{++}$) region by requiring $|M(\Lambda_c^+\pi^+) - m_{\Sigma_c^{++}}| < 5$ (18) MeV/c^2, where $m_{\Sigma_c^{++}}$ is the nominal mass of the $\Sigma_c(2455)^{++}$ or $\Sigma_c(2520)^{++}$. Figure 1 (a) shows the $M(\Lambda_c^+ K^- \pi^+)$ distribution for the $\Sigma_c(2455)^{++}$ signal region together with the same plot for the $\Sigma_c(2455)^{++}$ sideband region. Clear peaks corresponding to the $\Xi_c(2980)^+$, $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ are seen. To obtain the statistical significance of the $\Xi_c(3055)^+$, an un-binned extended maximum likelihood (UML) fit is applied. PDFs for the Ξ_c^* components are represented by a Breit-Wigner line-shape convolved with a Gaussian to account for the invariant-mass resolution. The background shape is assumed to be threshold function. To estimate the statistical significance of the $\Xi_c(3055)^+$, we evaluate the likelihood ratio $-2\ln(\mathscr{L}_0/\mathscr{L})$, where $\mathscr{L}_0$ is the likelihood for the fit without signal and $\mathscr{L}$ is likelihood for the fit with the signal taking into account the change of number of degrees of freedom. The statistical significance of the $\Xi_c(3055)^+$ is 6.8σ.

Figure 1 (b) shows the $M(\Lambda_c^+ K^- \pi^+)$ distribution for the $\Sigma_c(2520)^{++}$ selected region together with the same plot for the $\Sigma_c(2520)^{++}$ sideband region. A clear peak corresponding to the $\Xi_c(3080)^+$ is seen, while no peak structure is seen in the mass near 3.123 GeV/c^2. An UML fit is applied to extract the signal yield. Again, the Ξ_c^* components are represented by a Breit-Wigner function convolved with a Gaussian. For the $\Xi_c(3080)^+$ component, the mass and width of the Breit-Wigner are treated as free parameters; while for the $\Xi_c(3123)^+$ component, the mass and width are fixed to the values obtained in Ref.[2]. The background shape is assumed to be threshold function. The yield of the $\Xi_c(3123)^+$ is 8 ± 22 events, which is consistent with zero. Hence, a 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,

$$\sigma_{\mathscr{B}\Lambda_c^+} \equiv \sigma(e^+e^- \to \Xi_c(3123)^+ X) \times \mathscr{B}(\Lambda_c^+ \to pK^-\pi^+)$$

is evaluated with the Bayesian approach. As in Ref. [2], we assume $\mathscr{B}(\Xi_c(3123)^+ \to \Sigma_c(2520)^{++}K^-)$ is equal to 1. The upper limit on $\sigma_{\mathscr{B}\Lambda_c^+}$ is 0.34 fb. The value is much smaller than that quoted in Ref. [2] ($1.6 \pm 0.6 \pm 0.2$ fb). The systematic uncertainties of the masses and widths of the Ξ_c^* and stability of the statistical significance of the $\Xi_c(3055)^+$ are studied by changing various fit conditions. In none of these fitting configurations does the statistical significance of the $\Xi_c(3055)^+$ fall below 6.6σ. The measured mass and width of the Ξ_c^* states are summarized in Table 1.

3.2 Results for $\Lambda D^{+(0)}$ final state

Figure 2 shows the $M(\Lambda D^{+(0)})$ distribution, where peak structures near 3055 MeV/c^2 and 3080 MeV/c^2 are seen. In order to check the existence of the peaking structure in the background, we check invariant mass distribution of the wrong-sign combination $\overline{\Lambda}D$, Λ and D for the sideband

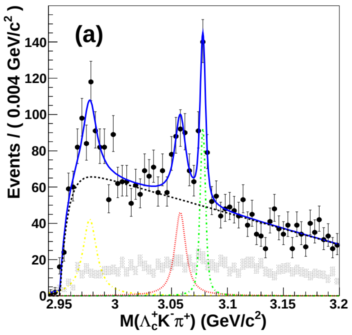

Figure 1: (a) The $M(\Lambda_c^+ K^- \pi^+)$ distribution with $\Sigma_c(2455)^{++}$ selection. The dots with error bars show the distribution for the $\Sigma_c(2455)^{++}$ selected whereas the rectangles show the distribution for the $\Sigma_c(2455)^{++}$ sideband region. Blue line shows the fit result. 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.

region the D candidates. None of them show a peaking structure. Therefore, these peaks are very likely to be corresponding to two known Ξ_c^* states, $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$.

We perform UML fit to mass spectra again. PDFs for a Ξ_c^* components are represented by Breit-Wigner line-shapes convolution with Gaussian. The mass and the width of the Ξ_c^* states are treated as free parameters. The third order Chebychev function is used to model the combinatorial background shape. 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 $\Xi_c(3055)^0$ ($\Xi_c(3080)^0$). The systematic uncertainty of the mass and width are evaluated by changing various fit conditions. The measured mass and width of the Ξ_c^* states are summarized in Table 1.

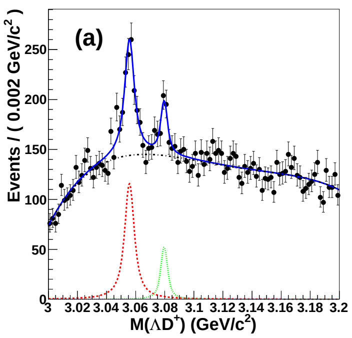

Figure 2: (a):$M(D^+\Lambda)$ distribution. (b):$M(D^0\Lambda)$ distribution. Blue line shows the fitting result. Black, red, and green lines show the background, $\Xi_c(3055)^{+/0}$, and $\Xi_c(3080)^{+/0}$ components, respectively.

Table 1: The measured masses and widths of the Ξ_c^{*+} states. The first error is statistical and second is systematic.

Particle	Mass (MeV/c^2)	Width (MeV)
$\Xi_c(2980)^+$	$2974.9 \pm 1.5 \pm 2.1$	$14.8 \pm 2.5 \pm 4.1$
$\Xi_c(3055)^+(\Sigma_c(2455))$	$3058.1 \pm 1.0 \pm 2.1$	$9.7 \pm 3.4 \pm 3.3$
$\Xi_c(3080)^+(\Sigma_c(2455))$	$3077.9 \pm 0.4 \pm 0.7$	$3.2 \pm 1.3 \pm 1.3$
$\Xi_c(3080)^+(\Sigma_c(2520))$	$3076.9 \pm 0.3 \pm 0.2$	$2.4 \pm 0.9 \pm 1.6$
$\Xi_c(3055)^+(\Lambda D^+)$	$3055.7 \pm 0.4 \pm 0.4$	$7.1 \pm 1.2 \pm 1.8$
$\Xi_c(3080)^+(\Lambda D^+)$	$3079.6 \pm 0.6 \pm 0.7$	$4.0 \pm 1.5 \pm 1.0$
$\Xi_c(3055)^0(\Lambda D^0)$	$3059.7 \pm 0.6 \pm 0.5$	$7.4 \pm 1.9 \pm 3.4$
$\Xi_c(3080)^0(\Lambda D^0)$	$3081.6 \pm 1.1 \pm 0.2$	$4.4 \pm 1.8 \pm 1.9$

4. Summary

We report studies of charmed strange baryons in the $\Lambda_c^+ K^- \pi^+$ and $\Lambda D^{+(0)}$ final states. We have searched for the $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ in the $\Lambda_c^+ K^- \pi^+$ decays through intermediate $\Sigma_c(2455)^{++}$ or $\Sigma_c(2520)^{++}$ states. We observe the $\Xi_c(3055)^+$ while we do not observe any significant signal corresponding to the $\Xi_c(3123)^+$. We also report first observation of $\Xi_c(3055)^{+(0)}$ and $\Xi_c(3080)^+$ decay in the $\Lambda D^{+(0)}$ final states. Especially, this is the first observation of the $\Xi_c(3055)^0$.

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