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 $\Xi_c(3055)^0$.
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 ($\Xi^*$) 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 $\Lambda_c^+ K^0 \pi^-$ 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 $\Lambda_c^+$ 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 ($r$-$\phi$) direction and within 2 cm along the $z$-axis. (The $z$-axis is opposite the positron beam direction.) For each track, the likelihood values $L_p$, $L_K$, and $L_{\pi}$ are provided for the assumption of proton, kaon and pion, respectively. The likelihood ratio is defined as $L(i : j) = L_i / (L_i + L_j)$ and a track is identified as a proton if the likelihood ratios $L(p : \pi)$ and $L(p : K)$ are greater than 0.6. A track is identified as a kaon if the likelihood ratios $L(K : \pi)$ and $L(K : p)$ are greater than 0.6. A track is identified as a pion if the likelihood ratios $L(\pi : K)$ and $L(\pi : p)$ are greater than 0.6. In addition, electron ($L_e$) 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 $\pi^0$ 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 $\pi^0$ candidate is required to be greater than 500 MeV/$c^2$. The $\Lambda$ candidates are selected based on their decay vertex information [6] and invariant mass of a $\Lambda$ candidate is required to be within 3 MeV/$c^2$ of the nominal $\Lambda$ mass, which corresponds to approximately 3$\sigma$ 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$\sigma$ of the mass resolution, is selected. The $\Lambda_c^+$ ($D^{+(0)}$) candidates are selected by requiring invariant mass of the daughter particles to be within 1.5 (2.0)$\sigma$ of the nominal mass. The $\chi^2$ value of the common vertex fit of the $\Lambda_c^+$ or $D^{+(0)}$ is required to be less than 50. For the remaining candidate, a mass constraint fit to the $\Lambda_c^+$ 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 $\Xi_c^+$ candidate and $s$ is CM energy squared and $m$ is mass of the $\Xi_c^+$ 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 $\Sigma_c(2520)^{++}$ 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 $\Xi_c^+$ 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 $-2\ln(\mathcal{L}_0/\mathcal{L})$, where $\mathcal{L}_0$ is the likelihood for the fit without signal and $\mathcal{L}$ 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 6.8$\sigma$.

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 $\Xi_c^+$ 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 $\Lambda_c^+$ produced with $x_p > 0.7$ condition,

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

is evaluated with the Bayesian approach. As in Ref. [2], we assume $\mathcal{B}(\Xi_c(3123)^+ \rightarrow \Sigma_c(2520)^{++}K^-)$ is equal to 1. The upper limit on $\sigma_{\Lambda_c^+}$ is 0.34 fb. The value is much smaller than that quoted in Ref. [2] (1.6 ± 0.6 ± 0.2 fb). The systematic uncertainties of the masses and widths of the $\Xi_c^+$ 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 6.6$\sigma$. The measured mass and width of the $\Xi_c^+$ 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 $\bar{\Lambda}D$, $\Lambda$ and $D$ for the sideband
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Figure 1: (a) The $M(\Lambda^+ K^- \pi^+)$ 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 $M(\Lambda^+ K^- \pi^+)$ distribution with $\Sigma_c(2520)^{++}$ selection. The dots with error bars show the distribution for the $\Sigma_c(2520)^{++}$ selected 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.

We perform UML fit to mass spectra again. PDFs for $\Xi_c^*$ components are represented by Breit-Wigner line-shapes convolution with Gaussian. The mass and the width of the $\Xi_c^*$ 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)$\sigma$ for $\Xi_c(3055)^+$ ($\Xi_c(3080)^+$) and 7.6 (2.6)$\sigma$ 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 $\Xi_c^*$ 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.
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Table 1: The measured masses and widths of the $\Xi_c^{++}$ states. The first error is statistical and second is systematic.

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

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 $\Xi_c(3080)^+(0)$ decay in the $\Lambda D^{+(0)}$ final states. Especially, this is the first observation of the $\Xi_c(3055)^0$.

References

[5] Throughout this paper, the inclusion of the charge-conjugate decay mode is implied unless otherwise stated.