Observation of New States Decaying into $\Lambda_c^+ K^- \pi^+$ and $\Lambda_c^+ K_S^0 \pi^-$

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We report the first observation of two charmed strange baryons that decay into $\Lambda_c^+ K^- \pi^+$. The broader of the two states is measured to have a mass of $2978.5 \pm 2.1 \pm 2.0\ \mathrm{MeV}/c^2$ and a width of $43.5 \pm 7.5 \pm 7.0\ \mathrm{MeV}/c^2$. The mass and width of the narrow state are measured to be $3076.7 \pm 0.9 \pm 0.5\ \mathrm{MeV}/c^2$ and $6.2 \pm 1.2 \pm 0.8\ \mathrm{MeV}/c^2$, respectively. We also perform a search for the isospin partner states that decay into $\Lambda_c^+ K_S^0 \pi^-$ and observe a significant signal at the mass of $3082.8 \pm 1.8 \pm 1.5\ \mathrm{MeV}/c^2$. The data used for this analysis were accumulated at or near the $\Upsilon(4S)$ resonance, using the Belle detector at the e^+e^- asymmetric-energy collider KEKB. The integrated luminosity of the data sample used is $461.5\ \mathrm{fb}^{-1}$.

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Several excited Λ_c^+ [1], Σ_c [2], and Ξ_c [3] baryons have already been observed. The most recent examples are an isotriplet of excited Σ_c baryons and the $\Lambda_c(2940)^+$, reported by Belle and *BABAR*, respectively [4]. The charmed baryon sector offers a rich source of states and possible orbital excitations, serving as an excellent laboratory to test the predictions of the quark model and other models of bound quarks [5], as well as predictions based on heavy quark symmetry [6]. New experimental information on charmed baryon excited states could also be useful for further development of approaches based on lattice QCD [7]. Some of the recently discovered baryons are candidates for orbitally excited states [8]. Within the Ξ_c system, two candidates for the first P-wave orbital excitations were found, the $\Xi_c(2790)$ and $\Xi_c(2815)$ baryons, which decay into $\Xi_c' \pi$ and $\Xi_c^* \pi$, respectively [9,10]. In these decays, the charm and strange quarks of the initial state are inherited by the final state baryon. However, nothing is experimentally known about charmed strange baryons that decay to $\Lambda_c^+ K^- \pi^+$. The invariant mass threshold for this final state is above the previously known charmed baryons that could exhibit such a decay with a significant rate. In such a decay processes, the charm and strangeness of the initial state are carried away by two different final state particles, a charmed baryon and a strange meson.

The SELEX Collaboration has reported the observation of a doubly charmed baryon that decays into the $\Lambda_c^+ K^- \pi^+$ final state [11]. The SELEX claim has not been confirmed by other experiments. The measured cross section for $c\bar{c}c\bar{c}$ production [12] is an order of magnitude larger than nonrelativistic QCD predictions [13]. This $c\bar{c}c\bar{c}$ mechanism could lead to a relatively high production rate of doubly charmed baryons in e^+e^- collisions and hence represents an additional motivation for the examination of the $\Lambda_c^+ K^- \pi^+$ final state.

In this Letter we report the results of a search for new baryons decaying into $\Lambda_c^+ K^- \pi^+$ and $\Lambda_c^+ K_S^0 \pi^-$ final states. Inclusion of charge conjugate states is implicit unless otherwise stated. The analysis is performed using data collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [14]. The data sample corresponds to an integrated luminosity of $461.5\ \mathrm{fb}^{-1}$ collected at or near the $\Upsilon(4S)$ resonance.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [15]. Two different inner detector configurations were used, a 2.0 cm beam pipe and a 3-layer silicon vertex detector for the first 155 fb^{-1}, and a 1.5 cm beam pipe with a 4-layer vertex detector for the remaining 306.5 fb^{-1} [16]. We use a GEANT-based Monte Carlo (MC) simulation to model the response of the detector and determine the efficiency [17].

Protons, charged pions, and kaons are required to originate from the region $dr < 1$ cm, $|dz| < 3$ cm. Here, dr and dz are the distances of closest approach to the interaction point in the plane perpendicular to the beam axis ($r - \phi$ plane) and along the beam direction, respectively. Charged hadrons are identified using a likelihood ratio method, which combines information from the TOF system and ACC counters with dE/dx measurements in the CDC. To identify charged particles (π, K, p), we apply the standard Belle requirements on the corresponding likelihood ratios [15]. Neutral kaons are reconstructed via the decay $K_S^0 \to \pi^+\pi^-$, requiring $M(\pi^+\pi^-)$ to be within ± 10 MeV/c^2 of the nominal K_S^0 mass [8]. We require the displacement of the $\pi^+\pi^-$ vertex from the interaction point in the $r - \phi$ plane to be more than 0.1 cm.

We reconstruct the Λ_c^+ via the $\Lambda_c^+ \to pK^-\pi^+$ decay channel. All $pK^-\pi^+$ combinations with an invariant mass within ± 10 MeV/c^2 ($\sim 2.5\sigma$) around 2286.6 MeV/c^2 are selected as Λ_c^+ candidates. The mean value of the mass for our Λ_c^+ signal is $2286.6 \pm 0.1(\text{stat.})$ MeV/c^2, in good agreement with a recent precision measurement by *BABAR* [18]. We perform a mass constrained fit to the Λ_c^+ vertex and then combine Λ_c^+ candidates with the remaining $K^-\pi^+$ pairs in the event.

The momentum spectra of charmed hadrons produced in $e^+e^- \to c\bar{c}$ continuum events are hard compared to the combinatorial background. Therefore, we apply the requirement $p^* > 3.0$ GeV/c, where p^* is the momentum of the $\Lambda_c^+ K^- \pi^+$ system in the center of mass frame. We also fit the $\Lambda_c^+ K^- \pi^+$ combinations to a common vertex.

The resulting invariant mass distribution $M(\Lambda_c^+ K^- \pi^+)$ is shown in Fig. 1(a). Two peaks are visible in this distribution: a broad one near threshold at a mass of about 2980 MeV/c^2 and a narrower one at a higher mass of about 3077 MeV/c^2. We verify that the observed signals are robust and their mass values stable against the variation of particle identification criteria, Λ_c^+ mass selection window, and the p^* requirement. Hereafter we denote the observed peaks as $\Xi_{cx}(2980)^+$ and $\Xi_{cx}(3077)^+$ as explained below.

Figure 1(b) shows the invariant mass distribution of the wrong-sign (WS) combinations $M(\Lambda_c^+ K^+ \pi^-)$, which has a smooth structureless behavior. This demonstrates that the observed peaks in the right-sign (RS) $M(\Lambda_c^+ K^- \pi^+)$ in-

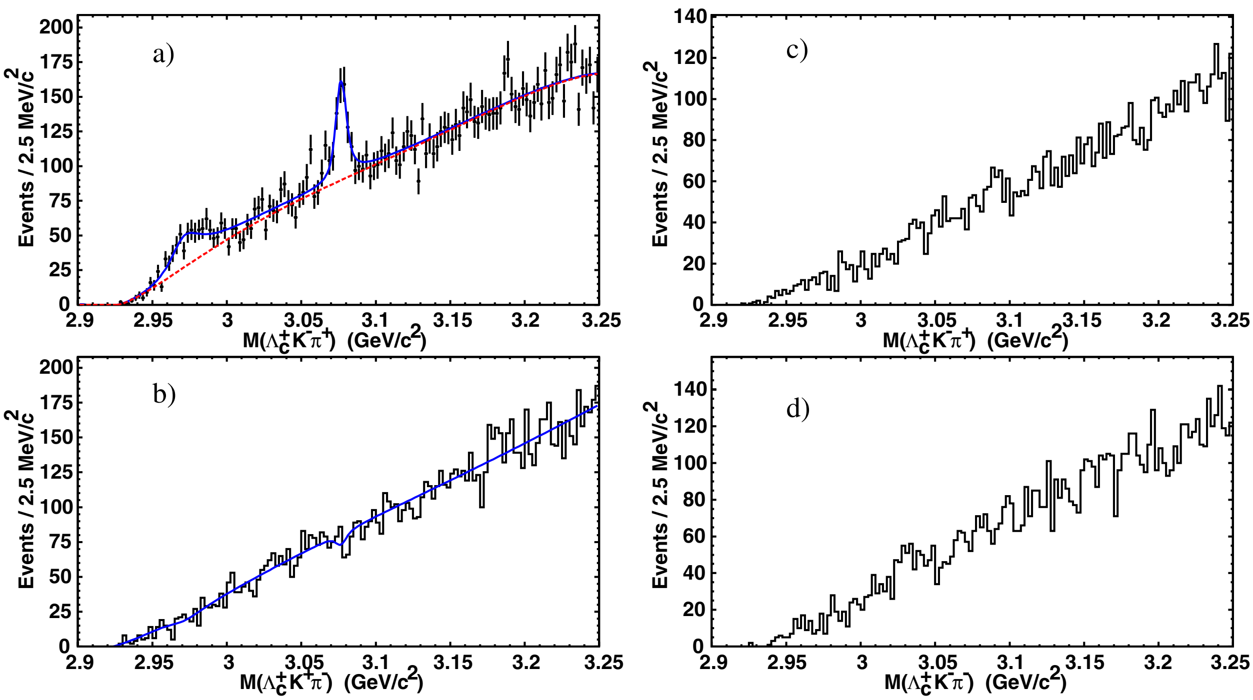

FIG. 1 (color online). (a) $M(\Lambda_c^+ K^- \pi^+)$ distribution together with the overlaid fitting curve. Points with errors represent the data, the dashed line is the background component of the fitting function described in the text, and the solid curve is the sum of the background and signal. (b) The WS combination mass distribution $M(\Lambda_c^+ K^+ \pi^-)$ fitted with the same function including the signal components where the masses and widths of the signals are fixed to the values from the fit to the RS distribution. Two additional cross-checks are shown (c) the invariant mass distribution of the right-sign $\Lambda_c^+ K^- \pi^+$ combinations but using appropriately scaled sidebands of the Λ_c^+ signal and (d) the invariant mass distribution of the other WS $\Lambda_c^+ K^- \pi^-$ combinations. No structures are visible in the signal regions near 2980 MeV/c^2 and 3077 MeV/c^2.

variant mass distribution are not reflections due to $K - \pi$ misidentification originating from the four known excited baryons $\Lambda_c(2593)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2765)^+$, and $\Lambda_c(2880)^+$ [1,8] that decay into $\Lambda_c^+\pi^+\pi^-$. Reflections from the $\Lambda_c^+\pi^+\pi^-$ decay modes of these states would contribute equally to both the RS and WS distributions. This conclusion is also verified with a MC simulation of $\Lambda_c(2593)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2765)^+$, and $\Lambda_c(2880)^+$ produced in $e^+e^- \to c\bar{c}$. We generate 10^4 $\Lambda_c^+\pi^+\pi^-$ decays for each excited Λ_c^+ state and reconstruct the MC events with the same selection criteria as the data. The resulting mass distributions exhibit similar behavior in both RS and WS cases. Simulation shows that the yield of excited Λ_c^+ baryons decaying to $\Lambda_c^+\pi^+\pi^-$ is reduced to 1.2% when using the above selection criteria, and that the possible reflections in the Ξ_{cx} signal mass region are negligible. Using the reconstruction of $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$ events with the same data set, we find that possible contribution of reflections is below the statistical sensitivity of our measurement.

Figure 1(c) shows an additional check of the $M(\Lambda_c^+K^-\pi^+)$ distribution of data events in the Λ_c^+ mass sidebands [19]. We also check the invariant mass distribution for the $\Lambda_c^+K^-\pi^-$ WS combination, shown in Fig. 1(d). Both distributions in Fig. 1(c) and 1(d) are featureless in the 2980 MeV$/c^2$ and 3077 MeV$/c^2$ mass regions.

Results of the fit to the $M(\Lambda_c^+K^-\pi^+)$ distribution are shown by the solid curve in Fig. 1(a). The simulated mass resolution of $\Xi_{cx}(2980) \to \Lambda_c^+K^-\pi^+$ is found to be 1.2 MeV$/c^2$, which is much smaller than the observed signal width. Therefore, the broad signal near the threshold is modeled by a Breit-Wigner function only. To describe the $\Xi_{cx}(3077)^+$ resonance we use a Breit-Wigner function convolved with a Gaussian detector resolution function. The width of the Gaussian (σ) is fixed from MC calculations to be 2.0 MeV$/c^2$. The background is described by a threshold function $\mathrm{atan}(\sqrt{x - x_{\mathrm{thr}}})$ multiplied by a third-order polynomial. The dashed line in Fig. 1(a) shows the background component of the fitting function. The results of the fit are summarized in Table I. The χ^2/ndf of the fit is 0.98. The statistical significance of each of the two observed signals is defined as $\sqrt{-2\ln(L_0/L_{\max})}$. Here, L_0 and $L_{\max}$ are the values of the likelihood function with the corresponding signal fixed to zero and at the best fit value, respectively. The extraction of the significance assumes a simultaneous determination of three parameters for the signal—the mass, width, and yield. We fit the WS mass distribution using the same functional form, with parameters describing the shape of the signal fixed to the above values. The fit yields -34.8 ± 19.6 (-78.2 ± 54.6) events for the higher (lower) mass peak, consistent with zero.

To provide more information on the origin of the states found in the present analysis, we perform a search for their neutral isospin partners in the $\Lambda_c^+K_S^0\pi^-$ final state. In this case the selection criteria are the same as for the $\Lambda_c^+K^-\pi^+$ final state with one exception: a tighter momentum requirement, $p^* > 3.5$ GeV$/c$, is applied for the $\Lambda_c^+K_S^0\pi^-$ system. The resulting invariant mass distribution, $M(\Lambda_c^+K_S^0\pi^-)$, is shown in Fig. 2(a), where a clear signal near 3077 MeV$/c^2$ is observed. A broad enhancement near the threshold can also be identified. Figure 2(b) shows the WS $M(\Lambda_c^+K_S^0\pi^+)$ distribution, which is featureless. To describe the narrow signal, which we denote as $\Xi_{cx}(3077)^0$, we use a Breit-Wigner function convolved with a Gaussian detector resolution function. The width of the Gaussian is fixed from MC calculations to be $\sigma =$ 2.4 MeV$/c^2$. To describe the broad signal near the threshold which we denote as $\Xi_{cx}(2980)^0$ we use a Breit-Wigner function with the width fixed to that of $\Xi_{cx}(2980)^+$, $\Gamma =$ 43.5 MeV$/c^2$. The background is described by a threshold function multiplied by a third-order polynomial. The signal yields and parameters of the two Breit-Wigner functions determined from the fit are given in Table I.

We also vary the order of the polynomial for the background function and the widths of the detector resolution within their errors. The resulting systematic uncertainties are given in Table I. None of the variations reduces the significances of the $\Xi_{cx}(3077)^+$, $\Xi_{cx}(2980)^+$, and $\Xi_{cx}(3077)^0$ to less than 9σ, 5σ, and 4σ, respectively.

The SELEX Collaboration reported the observation of a doubly charmed baryon with a mass of 3520 MeV$/c^2$ in the $\Lambda_c^+K^-\pi^+$ final state [11]. We extend the range of the $M(\Lambda_c^+K^-\pi^+)$ search to include the region surrounding 3520 MeV$/c^2$ (Fig. 3). To compare the yield to the inclusive production of Λ_c^+, we modify the momentum requirement to $p^* > 2.5$ GeV$/c$ only for the Λ_c^+ baryon. We find no evidence for a signal either at this mass or in a wide range around it. The overlaid curve in Fig. 3 is the result of the fit. To describe a possible signal we use a Gaussian resolution function with the width fixed to the signal MC

TABLE I. Summary of the parameters of the new states in the $\Lambda_c^+K^-\pi^+$ and $\Lambda_c^+K_S^0\pi^-$ final states: masses, widths, yields and statistical significances.

New State	Mass (MeV$/c^2$)	Width (MeV$/c^2$)	Yield (events)	Significance (σ)
$\Xi_{cx}(2980)^+$	$2978.5 \pm 2.1 \pm 2.0$	$43.5 \pm 7.5 \pm 7.0$	405.3 ± 50.7	5.7
$\Xi_{cx}(3077)^+$	$3076.7 \pm 0.9 \pm 0.5$	$6.2 \pm 1.2 \pm 0.8$	326.0 ± 39.6	9.2
$\Xi_{cx}(2980)^0$	$2977.1 \pm 8.8 \pm 3.5$	43.5 (fixed)	42.3 ± 23.8	1.5
$\Xi_{cx}(3077)^0$	$3082.8 \pm 1.8 \pm 1.5$	$5.2 \pm 3.1 \pm 1.8$	67.1 ± 19.9	4.4

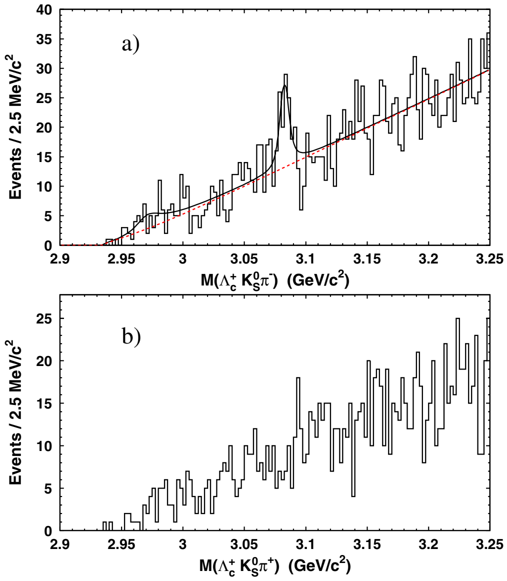

FIG. 2 (color online). (a) $M(\Lambda_c^+ K_S^0 \pi^-)$ distribution together with the overlaid fitting curve. The fitting function is the same as in the $\Lambda_c^+ K^- \pi^+$ case (see the text). (b) The WS combination mass distribution $M(\Lambda_c^+ K_S^0 \pi^+)$.

value of 4.9 MeV$/c^2$. The background is parametrized by a third-order polynomial function. From the fit, we obtain an upper limit of 69.1 events at 90% confidence level (C.L.) When the same selection criteria are applied for the inclusive Λ_c^+ ($p^* > 2.5$ GeV$/c$) production, we reconstruct $(83.5 \pm 1.4) \times 10^4$ Λ_c^+ decays. Taking into account the ratio of the total reconstruction efficiencies, we derive an upper limit on the ratio of production cross sections with $p^*(\Lambda_c^+) > 2.5$ GeV$/c$, $\sigma(\Xi_{cc}(3520)^+) \times \mathcal{B}(\Xi_{cc}(3520)^+ \to \Lambda_c^+ K^- \pi^+)/\sigma(\Lambda_c^+) < 1.5 \times 10^{-4}$ at 90% C.L. Recently, the *BABAR* Collaboration has also performed an extensive search for doubly charmed baryons. They set an upper limit of 2.7×10^{-4} at 95% C.L. [20] for the same decay process taking account of the efficiency of the p^* requirement.

In conclusion, we report the first observation of two charged baryons $\Xi_{cx}(2980)^+$ and $\Xi_{cx}(3077)^+$ decaying into $\Lambda_c^+ K^- \pi^+$. We also search for neutral isospin-related partners in the $\Lambda_c^+ K_S^0 \pi^-$ final state and observe a signal for the $\Xi_{cx}(3077)^0$. The masses and widths of all the observed states are summarized in Table I. Taking into account the presence of s and c quarks in the final state and the observation of an isospin partner near 3077 MeV$/c^2$ in the $\Lambda_c^+ K_S^0 \pi^-$ final state, the most natural interpretations of these states are that they are excited charmed strange baryons, Ξ_c. In contrast to decays of known excited Ξ_c states, the observed baryons decay into separate charmed (Λ_c^+) and strange (K) hadrons. Further studies of the properties of the observed states are ongoing. We have also searched for the doubly charmed baryon state at 3520 MeV$/c^2$ reported by the SELEX Collaboration in the $\Lambda_c^+ K^- \pi^+$ final state [11], and we extract an upper limit on its production cross section relative to the inclusive Λ_c^+ yield.

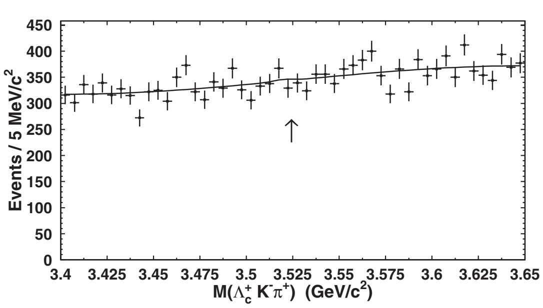

FIG. 3. The $M(\Lambda_c^+ K^- \pi^+)$ distribution near 3520 MeV$/c^2$ (indicated by an arrow), the mass of a possible doubly charmed baryon candidate [11].

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