Observation of an Isotriplet of Excited Charmed Baryons Decaying to $\Lambda_c^+ \pi$

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We report the observation of an isotriplet of excited charmed baryons, decaying into $\Lambda_c^+\pi^-$, $\Lambda_c^+\pi^0$, and $\Lambda_c^+\pi^+$. We measure the mass differences $M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ and widths to be $515.4^{+3.2+2.1}_{-3.1-6.0}$ MeV$/c^2$, 61^{+18+22}_{-13-13} MeV for the neutral state; $505.4^{+5.8+12.4}_{-4.6-2.0}$ MeV$/c^2$, 62^{+37+52}_{-23-38} MeV for the charged state; and $514.5^{+3.4+2.8}_{-3.1-4.9}$ MeV$/c^2$, 75^{+18+12}_{-13-11} MeV for the doubly charged state, where the uncertainties are statistical and systematic, respectively. These results are obtained from a 281 fb^{-1} data sample collected with the Belle detector near the $\Upsilon(4S)$ resonance, at the KEKB asymmetric energy e^+e^- collider.

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Charmed baryon spectroscopy provides an excellent laboratory to study the dynamics of a light diquark in the environment of a heavy quark, allowing the predictions of different theoretical approaches to be tested [1]. The baryons containing one c quark and two light (u or d) quarks are denoted Λ_c and Σ_c for states with isospin zero and one, respectively. All known excited charmed baryons decay into $\Lambda_c^+\pi$ and $\Lambda_c^+\pi\pi$ final states. There are four excited charmed baryons observed in the $\Lambda_c^+\pi^+\pi^-$ final state [2]; the lower two are identified as orbital excitations of Λ_c^+ while the upper two are not yet identified. In the $\Lambda_c^+\pi$ final state, only the $\Sigma_c(2455)$ ground state and the $\Sigma_c(2520)$ spin excitation have been observed so far, while the orbital excitations of the Σ_c remain to be found. In this Letter we present the results of a search for new states decaying into a Λ_c^+ baryon and a charged or neutral pion. This study is performed using a data sample of 253 fb^{-1} collected at the $\Upsilon(4S)$ resonance and 28 fb^{-1} at an energy 60 MeV below the resonance. The data were collected with the Belle detector [3] at the KEKB asymmetric energy e^+e^- storage rings [4].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer cylindrical drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like array of time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals (ECL) located inside a superconducting solenoidal coil that produces a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect muons and K_L^0 mesons (KLM). Two different inner detector configurations were used. For the first sample of 155 fb^{-1}, a 2.0 cm radius beampipe and a 3-layer silicon vertex detector were used; for the latter sample of 126 fb^{-1}, a 1.5 cm radius beampipe and a 4-layer silicon vertex detector and a small-cell inner drift chamber were used [5]. We use a GEANT based Monte Carlo (MC) simulation to model the response of the detector and to determine its acceptance. Signal MC events are produced with run dependent conditions and correspond to relative luminosities of different running periods.

Λ_c^+ baryons are reconstructed using the $pK^-\pi^+$ decay mode (the inclusion of charge conjugate modes is implied throughout this Letter). Charged hadron candidates are required to originate from the vicinity of the run-averaged interaction point. For charged particle identification (PID), the combined information from CDC (dE/dx), TOF, and ACC is used. Protons, charged kaons, and pions are selected with PID criteria that have efficiencies of 83%, 84%, and 90%, respectively (the PID criteria are not applied for pions originating from Λ_c^+ decays). The PID criteria reduce the background to 3%, 13%, and 53%, respectively. In addition, we remove charged hadron candidates if they are consistent with being electrons based on the ECL, CDC, and ACC information. We define the signal window around the Λ_c^+ mass to be ± 8 MeV$/c^2$, which corresponds to an efficiency of about 90% (1.6σ).

A pair of calorimeter showers with an invariant mass within 10 MeV$/c^2$ (1.6σ) of the nominal π^0 mass is considered as a π^0 candidate. An energy of at least 50 MeV is required for each shower.

To reduce the combinatorial background in Λ_c^+ and $\Lambda_c^+\pi$ resonance reconstruction, we impose a requirement on the scaled momentum $x_p \equiv p^*/p^*_{\rm max}$, where p^* is the momentum of the charmed baryon candidate in the center of mass (c.m.) frame, and $p^*_{\rm max} \equiv \sqrt{E^{*2}_{\rm beam} - M^2}$; $E^*_{\rm beam}$ is the beam energy in the c.m. frame, and M is the mass of the candidate. To allow a comparison of our Λ_c^+ sample with that of other experiments and to demonstrate its high purity, we apply a $x_p > 0.5$ requirement on Λ_c^+ candidates. The Λ_c^+ yield with this requirement is $(516 \pm 2) \times 10^3$ and the signal-to-background ratio is 2.3.

We combine Λ_c^+ candidates with the remaining pion candidates in the event. The x_p requirement on the Λ_c^+ candidate is released, and a $x_p > 0.7$ requirement on the $\Lambda_c^+\pi$ pair is applied. The tight x_p cut is justified by the hardness of the momentum spectra of known excited charmed baryons. To further suppress the combinatorial background from low momentum pions, we require the decay angle $\theta_{\rm dec}$ to satisfy $\cos\theta_{\rm dec} > -0.4$. $\theta_{\rm dec}$ is defined as the angle between the π momentum measured in the rest frame of the $\Lambda_c^+\pi$ system and the boost direction of the $\Lambda_c^+\pi$ system in the c.m. frame. The requirement $\cos\theta_{\rm dec} > -0.4$ is chosen assuming a flat $\cos\theta_{\rm dec}$ distribution for the signal.

Figure 1 shows distributions of the mass difference $\Delta M(\Lambda_c^+\pi) \equiv M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ for the $\Lambda_c^+\pi^-$, $\Lambda_c^+\pi^0$, and $\Lambda_c^+\pi^+$ combinations in the region above the $\Sigma_c(2455)$ and $\Sigma_c(2520)$ resonances. All the distributions show enhancements near 0.51 GeV$/c^2$, which we interpret as signals of new excited charmed baryons, forming an isotriplet. The new baryons are hereafter denoted as $\Sigma_c(2800)^0$, $\Sigma_c(2800)^+$, and $\Sigma_c(2800)^{++}$ for the three final states, respectively. Scaled Λ_c^+ sidebands, which are also shown in Fig. 1, exhibit featureless ΔM distributions. We also check the $\Delta M(\Lambda_c^+\pi)$ spectra for $e^+e^- \to c\bar{c}$ MC events, and find no enhancement in our signal region.

The enhancement near $\Delta M = 0.43$ GeV$/c^2$ in the $\Delta M(\Lambda_c^+\pi^-)$ and $\Delta M(\Lambda_c^+\pi^+)$ spectra is attributed to feed-down from the decay $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$. The $\Lambda_c(2880)^+$ resonance was observed by CLEO [6] in the $\Lambda_c^+\pi^+\pi^-$ final state; 30% of decays proceed via an intermediate $\Sigma_c(2455)^0$ or $\Sigma_c(2455)^{++}$. From a MC study we find that if $\Lambda_c^+\pi^\pm$ pairs are produced from intermediate $\Sigma_c(2455)^{++/0}$, then the $\Delta M(\Lambda_c^+\pi^\mp)$ spectrum is peaked around 0.43 GeV$/c^2$. To determine the yield of the feed-down we reconstruct the $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$ decays: selected $\Lambda_c^+\pi^\mp$ pairs are combined with all remaining pions $\pi^\pm_{\rm rem}$ in the event. We observe clear peaks of $\Lambda_c(2880)^+$ and $\Lambda_c(2765)^+$, consistent with the observation of these states by CLEO. We then fit the $\Delta M(\Lambda_c^+\pi^\mp\pi^\pm_{\rm rem}) \equiv M(\Lambda_c^+\pi^\mp\pi^\pm_{\rm rem}) - M(\Lambda_c^+)$ spectra to obtain the $\Lambda_c(2880)^+$ yield in bins of $\Delta M(\Lambda_c^+\pi^+_{\rm rem})$ and $\Delta M(\Lambda_c^+\pi^-_{\rm rem})$. The results of the fits are shown in Fig. 2. Each distribution shows a peak in the second bin due to an intermediate $\Sigma_c(2455)$ state. The fitting function, shown in Fig. 2, includes both resonant and nonresonant contributions and is determined from the MC simulation. The result of this fit is used to determine the $\Sigma_c(2455)^{++/0}$ fractions in $\Lambda_c(2880)^+$ decay, and thus the shape of the $\Lambda_c(2880)^+$ feed-down to the $\Lambda_c^+\pi^\mp$ distributions. In this calculation, we correct the feed-down normalization for the efficiency of $\pi^\pm_{\rm rem}$ reconstruction.

For the $\Lambda_c^+\pi^0$ final state, we expect a feed-down from the $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^0\pi^0$ decay. If the $\Lambda_c(2880)^+$ isospin is zero, then the following relations are valid: $\mathcal{B}(\Lambda_c(2880)^+ \to \Lambda_c^+\pi^0\pi^0) = 0.5\mathcal{B}(\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-)$ and $\mathcal{B}(\Lambda_c(2880)^+ \to \Sigma_c(2455)^+\pi^0) = \mathcal{B}(\Lambda_c(2880)^+ \to \Sigma_c(2455)^{++}\pi^-) = \mathcal{B}(\Lambda_c(2880)^+ \to \Sigma_c(2455)^0\pi^+)$. We do not observe the $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^0\pi^0$ decay due to the lower reconstruction efficiency for π^0, compared to $\pi^\pm$ (the expected signal yield is about 100 events, while the square root of the background is 110). Therefore, the shape and normalization of the $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^0\pi^0$ feed-down is determined based on the $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$ feed-down and the above

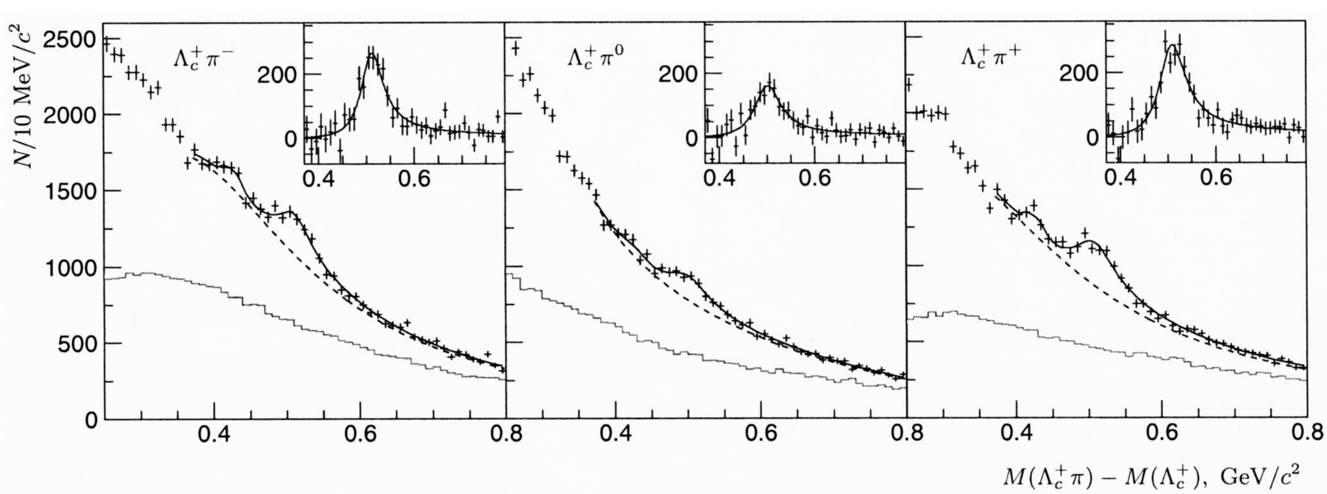

FIG. 1. $M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ distributions of the selected $\Lambda_c^+\pi^-$ (left), $\Lambda_c^+\pi^0$ (middle), and $\Lambda_c^+\pi^+$ (right) combinations. Data from the Λ_c^+ signal window (points with error bars) and normalized sidebands (histograms) are shown, together with the fits described in the text (solid curves) and their combinatorial background components (dashed). The insets show the background subtracted distributions in the signal region (points with error bars) with the signal component from the fit superimposed.

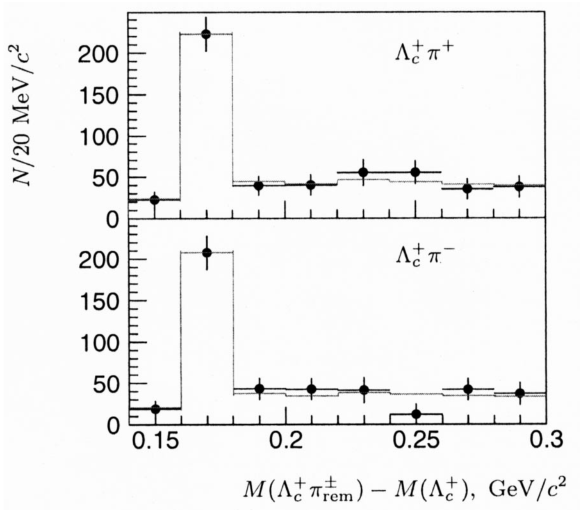

FIG. 2. Yield of $\Lambda_c(2880)^+$ vs $\Delta M(\Lambda_c^+\pi^+_{\rm rem})$ (top) and $\Delta M(\Lambda_c^+\pi^-_{\rm rem})$ (bottom). The peaks are due to intermediate $\Sigma_c(2455)^{++}$ and $\Sigma_c(2455)^0$ states, respectively, in $\Lambda_c(2880)^+$ decay: see the text.

isospin relations. We take into account the differences in the reconstruction efficiencies and mass resolutions for the $\Lambda_c^+\pi^0$ and $\Lambda_c^+\pi^\mp$ final states. If the $\Lambda_c(2880)^+$ isospin is one, then the $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^0\pi^0$ decay is forbidden. This possibility is taken into account as a systematic uncertainty.

We perform a fit to the $\Lambda_c^+\pi$ mass spectra of Fig. 1 to extract the parameters and yields of the $\Sigma_c(2800)^0$, $\Sigma_c(2800)^+$, and $\Sigma_c(2800)^{++}$. The fitting function is a sum of three components: signal, feed-down, and combinatorial background functions. We tentatively identify the $\Sigma_c(2800)$ states as Σ_{c2} baryons, decaying to $\Lambda_c^+\pi$ in D wave, so the signal is parametrized by a D-wave Breit-Wigner function (Blatt-Weisskopf form factors [7] are included), convolved with the detector resolution of 2 MeV$/c^2$ (7 MeV$/c^2$) for final states containing only charged (one neutral) pions. The shape and the normalization of the feed-down from $\Lambda_c(2880)^+$ is fixed as described above. The background is parametrized by an inverse third order polynomial $(1/\{C_0 + C_1x + C_2x^2 + C_3x^3\}$, where the C_i are floating parameters). The fit interval starts at 0.37 GeV$/c^2$ since at lower mass a feed-down from $\Lambda_c(2765)^+ \to \Lambda_c^+\pi^+\pi^-$ [6] is expected. The fits are shown in Fig. 1, and their results are summarized in Table I. The signal yield is defined as the integral of the Breit-Wigner function over the mass interval 0.34 GeV$/c^2 < \Delta M <$ 0.69 GeV$/c^2$ ($\sim 2.5\Gamma$).

The signal significances are 8.6, 6.2, and 10.0 standard deviations for $\Sigma_c(2800)^0$, $\Sigma_c(2800)^+$, and $\Sigma_c(2800)^{++}$, respectively. The significance is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_0$ and $\mathcal{L}_{\rm max}$ are the likelihood values returned by fits with the signal yield fixed at zero and the best fit values, respectively.

To estimate the systematic uncertainty on the results of the fit we vary the signal parametrization, using S-wave and P-wave Breit-Wigner functions. We vary the interval in ΔM used for the fit and the background parametrization, using polynomials and inverse polynomials of different orders, a function $(C_1 + C_2x)\exp(C_3x + C_4x^2)$, where the C_i are floating parameters, and these functions plus the normalized Λ_c^+ sidebands. We vary the normalization of the $\Lambda_c(2880)^+$ feed-down by $\pm 2\sigma$ and in the $\Lambda_c^+\pi^0$ case we also consider the possibility of zero feed-down. We tighten the x_p cut to 0.75 and we vary the $\cos\theta_{\rm dec}$ cut from -0.5 to -0.3. In each case we take the largest positive and negative variation in the fitted parameters as the systematic uncertainty from this source; each term is then added in quadrature to give the total systematic uncertainty. The dominant contribution originates from the variation of the interval used in the fit and the background parametrization. The parameters for the observed states with statistical and systematic uncertainties are summarized in Table I. For all background parametrizations, the signal significance exceeds 5.3σ in all final states. As a cross-check, we repeat the analysis using the $\Lambda_c^+ \to pK_S^0$ and $\Lambda\pi^+$ decay modes, and find consistent results. (We do not perform an average since the relative yields are low and the branching ratios of these modes relative to $\Lambda_c^+ \to pK^-\pi^+$ are poorly known.) We also check that the observed $\Sigma_c(2800)$ signals are not feed-downs from unknown resonances decaying to $\Lambda_c^+\pi\pi$ by combining $\Lambda_c^+\pi^\mp$ pairs from the $\Sigma_c(2800)$ region with all remaining $\pi^\pm$ in the event. The resulting $\Delta M(\Lambda_c^+\pi^+\pi^-)$ spectra exhibit no structure.

TABLE I. Signal yield, mass, and width for $\Sigma_c(2800)^0$, $\Sigma_c(2800)^+$, and $\Sigma_c(2800)^{++}$. The first uncertainty is statistical; the second one is systematic.

State	Yield$/10^3$	ΔM, MeV$/c^2$	Γ, MeV
$\Sigma_c(2800)^0$	$2.24^{+0.79+1.03}_{-0.55-0.50}$	$515.4^{+3.2+2.1}_{-3.1-6.0}$	61^{+18+22}_{-13-13}
$\Sigma_c(2800)^+$	$1.54^{+1.05+1.40}_{-0.57-0.88}$	$505.4^{+5.8+12.4}_{-4.6-2.0}$	62^{+37+52}_{-23-38}
$\Sigma_c(2800)^{++}$	$2.81^{+0.82+0.71}_{-0.60-0.49}$	$514.5^{+3.4+2.8}_{-3.1-4.9}$	75^{+18+12}_{-13-11}

To determine the efficiency of the $\cos\theta_{\rm dec} > -0.4$ requirement, we assume that the $\cos\theta_{\rm dec}$ distribution is symmetric about zero, as required by the conservation of P parity in strong decays. We check that the observed distributions are compatible with this assumption. We fit the $\Delta M(\Lambda_c^+\pi)$ spectra in the $0.4 < \cos\theta_{\rm dec} \le 1.0$ interval, fixing the signal parameters to the values obtained above and assuming the same background parametrization. The $\Lambda_c(2880)^+$ feed-down normalization is determined for the selected $\cos\theta_{\rm dec}$ interval. The reconstruction efficiency corrections are taken into account. The statistical uncertainty in the obtained signal yield is included in the systematic uncertainty of the efficiency.

To find the efficiency of the $x_p > 0.7$ requirement, we consider an extended interval $x_p > 0.5$ and fit the $\Delta M(\Lambda_c^+\pi)$ spectra in x_p bins. The $\Lambda_c(2880)^+$ feed-down normalization is determined in each x_p bin separately. The obtained efficiency-corrected x_p spectra are shown in

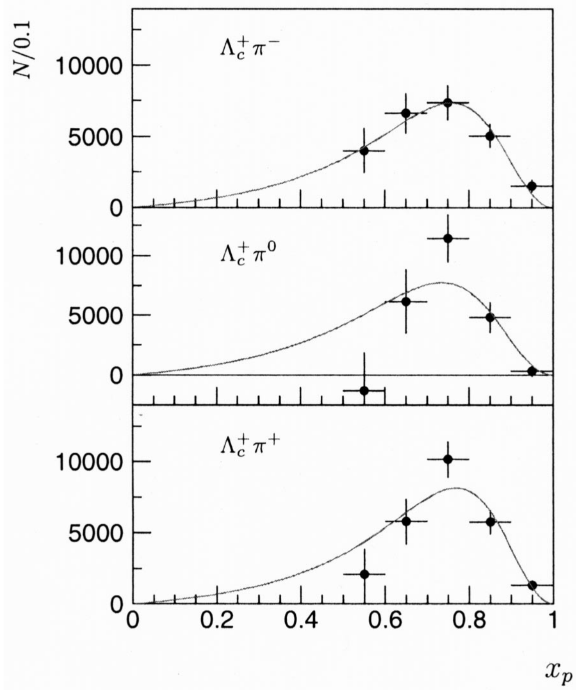

FIG. 3. Spectra of scaled momentum x_p for $\Sigma_c(2800)^0$ (top), for $\Sigma_c(2800)^+$ (middle), and for $\Sigma_c(2800)^{++}$ (bottom) states.

Fig. 3; the curves show fits using the Peterson [8] parametrization $dN/dx_p \sim x_p^{-1}[1 - 1/x_p - \epsilon/(1 - x_p)^2]^{-2}$. We obtain $\epsilon = 0.078^{+0.021}_{-0.017}$ for $\Sigma_c(2800)^0$, $\epsilon = 0.095^{+0.032}_{-0.024}$ for $\Sigma_c(2800)^+$, and $\epsilon = 0.069^{+0.015}_{-0.012}$ for $\Sigma_c(2800)^{++}$; these values are similar to other measurements for excited charmed baryons with nonzero orbital angular momentum [9]. The efficiency of the $x_p > 0.7$ requirement is calculated using the ϵ values from the fits. The statistical uncertainty in ϵ is included in the systematic uncertainty of the efficiency.

We calculate the product $\sigma[e^+e^- \to \Sigma_c(2800)X] \times \mathcal{B}[\Sigma_c(2800) \to \Lambda_c^+\pi]$ to be $(2.04^{+0.72+0.97}_{-0.50-0.52} \pm 0.53)$ pb for $\Sigma_c(2800)^0$, $(2.6^{+1.8+2.4}_{-1.0-1.5} \pm 0.7)$ pb for $\Sigma_c(2800)^+$, and $(2.36^{+0.69+0.64}_{-0.50-0.47} \pm 0.61)$ pb for $\Sigma_c(2800)^{++}$; the first uncertainty is statistical, the second is systematic, and the third is due to the uncertainty in the $\Lambda_c^+ \to pK^-\pi^+$ branching fraction.

Theoretical models predict a rich spectrum of excited charmed baryons in the vicinity of the observed states [10]. One of the candidates is a Σ_{c2} doublet with $J^P = 3/2^-$ and $5/2^-$, where the subscript 2 denotes the total angular momentum of the light quark system. The Σ_{c2} baryon is expected to decay principally into the $\Lambda_c^+\pi$ final state in D wave; the predicted mass difference $\Delta M = 500$ MeV$/c^2$ is close to that observed here, but the expected width $\Gamma \sim 15$ MeV [11] is smaller than the one we observe. However, we note that the $\Sigma_{c2}(J^P = 3/2^-)$ baryon can mix with the nearby $\Sigma_{c1}(J^P = 3/2^-)$, which would produce a wider physical state.

In summary, we report the observation of an isotriplet of excited charmed baryons, decaying into $\Lambda_c^+\pi^-$, $\Lambda_c^+\pi^0$, and $\Lambda_c^+\pi^+$. We measure the mass differences $M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ and widths to be $515.4^{+3.2+2.1}_{-3.1-6.0}$ MeV$/c^2$, 61^{+18+22}_{-13-13} MeV for the neutral state; $505.4^{+5.8+12.4}_{-4.6-2.0}$ MeV$/c^2$, 62^{+37+52}_{-23-38} MeV for the charged state; and $514.5^{+3.4+2.8}_{-3.1-4.9}$ MeV$/c^2$, 75^{+18+12}_{-13-11} MeV for the doubly charged state, where the uncertainties are statistical and systematic, respectively. We tentatively identify these states as members of the predicted Σ_{c2}, $J^P = 3/2^-$ isospin triplet.

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