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Confirmation of the Existence of the Σ_c^{++} and Λ_c^+ Charmed Baryons and Observation of the Decay $\Lambda_c^+ \rightarrow \Lambda\pi^+$ and $\bar{K}^0 p$

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In a broadband neutrino exposure of the Fermilab 15-ft bubble chamber, we observe the production of the $\Sigma_c^{++}(2426)$ charmed baryon followed by its decay to $\Lambda_c^+(2260)$ and π^+. We find the mass of the Λ_c^+ to be 2257±10 MeV and the $m(\Sigma_c^{++}) - m(\Lambda_c^+)$ mass difference to be 168±3 MeV. Previously unseen two-body decay modes of the $\Lambda_c^+(2260)$ are observed.

The first evidence for charm was the observation[1] of the J/ψ at Brookhaven National Laboratory (BNL) and Stanford Linear Accelerator Center (SLAC). This state is now identified as the spin-parity 1^- bound state of charmed quarks and antiquarks ($c\bar{c}$) and was thus the first case of "hidden charm." Dilepton production[2] by neutrinos has subsequently been shown to be a manifestation of bare charm. The first observation of a bare-charm state was made at BNL in a neutrino interaction in the 7-ft bubble chamber. This event was identified as the production of the isotriplet charmed-baryon state, $\Sigma_c^{++}(2426)$, and its decay to the isosinglet state, $\Lambda_c^+(2260)$.[3] These states were subsequently observed in photoproduction at Fermi National Accelerator Laboratory (FNAL),[4] and another example of the $\Lambda_c^+(2260)$ has recently been reported by Cnops *et al.* at BNL.[5] The bare-charmed-meson states, the $D(1865)$ and the $D^*(2005)$ were first seen by Goldhaber *et al.* in e^+e^- annihilations at SLAC,[6] and have since been confirmed in many other experiments at SLAC. These states have also been observed in neutrino interactions.[7]

In this Letter, we confirm the existence of the charmed baryons, obtain a measurement of their masses, and report the observation of previously unseen two-body decay modes of the Λ_c^+. The $\Sigma_c^{++}(2426)$ is detected through its decay into the $\Lambda_c^+(2260)$ and a π^+. The rate for $\Sigma_c^{++}(2426)$ production for various Λ_c^+ decay modes is also presented.

The experiment was carried out at the FNAL with use of the double-horn, focused, wideband muon-neutrino beam and the 15-ft bubble chamber filled with a heavy neon-hydrogen mixture (64 at.% neon). The results presented here are based on an analysis of the 134 000 photographs taken to date in the experiment.

The interaction length for hadrons in the heavy neon mix is 1.25 m (the chamber diameter is 3.7 m) so that hadrons produced in the neutrino interactions typically interact, while muons leave the chamber without interacting. Neutral strange particles are detected via their decays such as $K_s^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$. The film was scanned, and partially double scanned, for events with a possible neutral–strange-particle decay (a V^0). All such events were measured and geometrically reconstructed, and the decays were kinematically fitted using the programs TVGP and SQUAW. V^0's that made satisfactory two- or three-constraint kinematical fits to $K_s^0 \to \pi^+\pi^-$ or $\Lambda \to p\pi^-$ decays were retained. Kinematical ambiguities between the decays were resolved using the χ^2 probabilities of the fits and the center-of-mass–decay angular distributions. Events with an outgoing negative track with momentum greater than 2 GeV/c were taken to be charged-current interactions. We thus obtained a sample of 3141 $K_s^0 \to \pi^+\pi^-$ and 2297 $\Lambda \to p\pi^-$ decays in a total sample of ~100 000 charged-current neutrino interactions.

In a previous publication[7] (based on part of this data sample), we have reported the observation of the charmed D^0 meson through its decay into $\bar{K}^0\pi^+\pi^-$. We have also searched for the charmed baryon Λ_c^+ through its decay into $\Lambda\pi^+$, $\Lambda\pi^+\pi^+\pi^-$, $\bar{K}^0p$, and $\bar{K}^0p\pi^+\pi^-$ by examining the distributions in the effective masses of the decay products. No significant structure is visible in the $\bar{K}^0p$ and the $\bar{K}^0p\pi^+\pi^-$ mass distributions. Examination of the $\Lambda\pi^+$ and the $\Lambda\pi^+\pi^+\pi^-$ mass distributions (the $\Lambda\pi^+$ is shown in Fig. 1) shows small enhancements near the expected Λ_c^+ mass. However, the statistical significance of these enhancements is at most 2 standard deviations each.

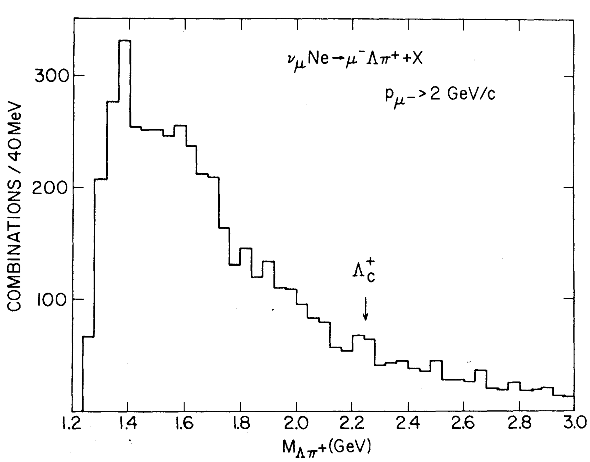

FIG. 1. Distributions in the $\Lambda\pi^+$ effective mass.

To investigate these structures near the Λ_c^+ mass, we consider the possibility that some of the Λ_c^+ events arise from the decays of a Σ_c^{++} into a Λ_c^+ and a π^+. Since the expected Q value for these decays is small, the resolution in the mass difference $\Delta m = m(\Sigma_c^{++}) - m(\Lambda_c^+)$ is very good (standard deviation $\sigma \sim 5$ MeV). In the first BNL charm event,[3] as well as in the FNAL photoproduction experiment,[4] the Λ_c^+ mass was 2260 MeV and the mass difference was near 166 MeV. Using these values as a guide, we select events with a $\Lambda\pi^+$ effective mass of 2260± 25 MeV in which there is at least one additional π^+. (25 MeV is our mass resolution.) The distribution in the mass difference, $\Delta m = m(\Lambda\pi^+\pi^+) - m(\Lambda\pi^+)$, shown in Fig. 2(a), shows clustering around 166 MeV. The Δm distributions for the mean of the control regions, with $m(\Lambda\pi^+)$ below and above the Λ_c^+ mass [Fig. 2(b)], show no clustering. The $\Lambda\pi^+$ mass distribution for events with Δm in the range of 166± 6 MeV is shown in Fig. 3(a). We observe 8 events at a mass of 2260 MeV, where we expect 1.5 events. The probability that this is a

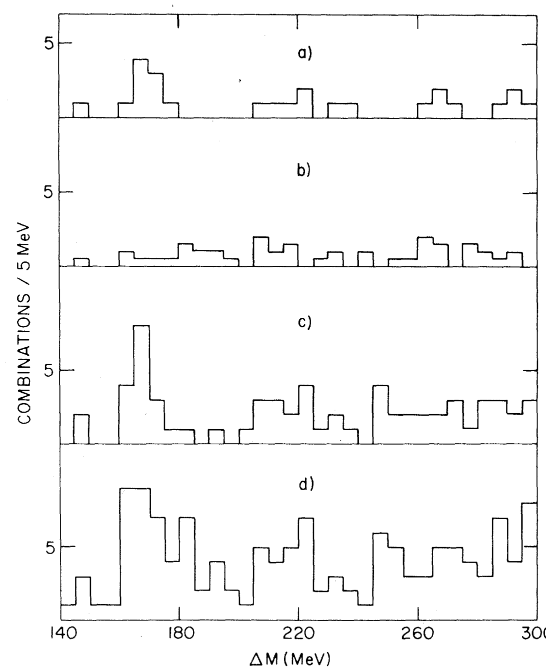

FIG. 2. Distribution (Ref. 9) in the mass difference Δm for (a) events in the Λ_c^+ region, $m(\Lambda\pi^+) = 2260\pm25$ MeV; (b) average of the control regions above and below the Λ_c^+ mass, $m(\Lambda\pi^+) = 2210\pm25$ MeV, and $m(\Lambda\pi^+) = 2310\pm25$ MeV, respectively; (c) events in the Λ_c^+ mass region, $m = 2260\pm25$ MeV, combined for $\Lambda\pi^+$ and $\bar{K}^0p$; (d) events in the Λ_c^+ mass region, $m = 2260\pm25$ MeV, combined for $\Lambda\pi^+$, $\bar{K}^0p$, $Y^{*+}\pi^+\pi^-$, and $K^{*-}p\pi^+$.

statistical fluctuation is $\sim 10^{-4}$. The $\Lambda\pi^+$ mass distributions for the mean of the control regions in Δm below and above 166 MeV, Fig. 3(b), have no peak at 2260 MeV. We consider this correlation between the $\Lambda\pi^+\pi^+$ and the $\Lambda\pi^+$ masses to be due to the production of the $\Sigma_c^{++}(2426)$, followed by its decay into $\Lambda_c^+(2260)\pi^+$, and subsequently, $\Lambda_c^+(2260) \to \Lambda\pi^+$. The Σ_c^{++} is manifestly exotic and the width of the Λ_c^+ is consistent with zero as would be expected for charmed baryons.

A similar analysis was carried out for three other possible Λ_c^+ decay modes into $\Lambda\pi^+\pi^+\pi^-$, $\bar{K}^0p$, and $\bar{K}^0p\pi^+\pi^-$. To reduce the large combinatorial background in the four-body modes, we have selected events where a $\Lambda\pi^+$ mass is in the $Y^*(1385)$ region (1382 ± 25 MeV), or a $\bar{K}^0\pi^-$ mass is in the $K^*(892)$ region (892 ± 32 MeV).[8] The distributions in Δm for the two-body Λ_c^+ decays, $\Lambda\pi^+$ and $\bar{K}^0p$ combined, are shown in Fig. 2(c), and the combined Δm distribution for all four decay modes is shown in Fig. 2(d). The combined $\Lambda\pi^+$ and $\bar{K}^0p$ mass distributions, selecting Δm to be in the range 166 ± 6 MeV, are shown in Fig. 3(c) while in Fig. 3(d) we further include the mass distributions for the channels $Y^{*+}(1385)\pi^+\pi^-$ and $K^{*-}p\pi^+$. We find a total of 20 events with mass (m) in the range 2260 ± 25 MeV and Δm in the range 166 ± 6 MeV with the breakdown given in Table I. Using the appropriate control regions in m and Δm, we expect a background of 6 events, where we observe 20. The probability of this being a statistical fluctuation is less than 10^{-5}.

In order to estimate the rates for Σ_c^{++} production followed by the decay $\Sigma_c^{++} \to \Lambda_c^+\pi^+$, with the Λ_c^+ decaying as above, we correct the number of these events observed above background by the V^0 branching ratios, the V^0 scan and detection efficiencies (76%), and the efficiency in the measurement and reconstruction of the charged tracks (87% per track). Normalizing this to the total number of charged-current interactions, we obtain the rates as given in Table I.

To obtain our best estimate of the Λ_c^+ mass and the Σ_c^{++}-Λ_c^+ mass difference, we use the 8

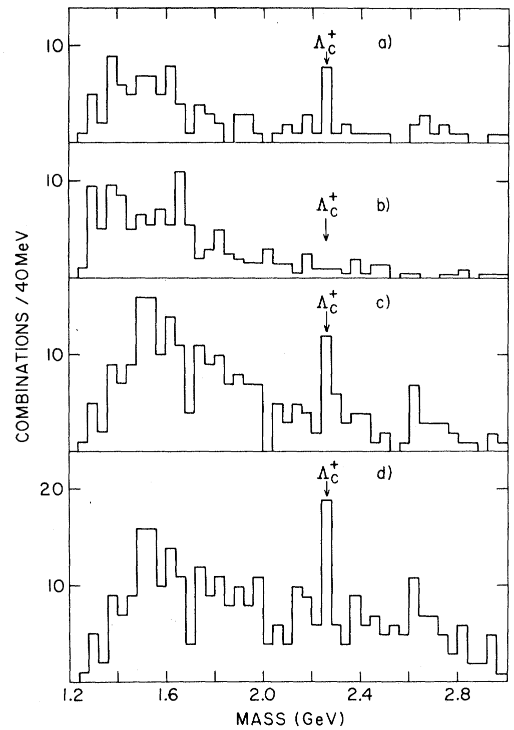

FIG. 3. (a) $\Lambda\pi^+$ invariant mass distribution (Ref. 9) for $\Delta m = 166 \pm 6$ MeV; (b) $\Lambda\pi^+$ invariant mass distribution for the average of the control regions at $\Delta m = 154 \pm 6$ MeV and $\Delta m = 178 \pm 6$ MeV; (c) combined $\Lambda\pi^+$ and $\bar{K}^0p$ mass distribution for $\Delta m = 166 \pm 6$ MeV; (d) combined $\Lambda\pi^+$, $\bar{K}^0p$, $Y^{*+}\pi^+\pi^-$, and $K^{*-}p\pi^+$ mass distributions for $\Delta m = 166 \pm 6$ MeV.

TABLE I. Observed events of the type $\nu\mathrm{Ne} \to \mu^- \Sigma_c^{++} + \cdots$, $\Sigma_c^{++} \to \Lambda_c^+\pi^+$ with 2.235 GeV < 2.285 GeV and 160 MeV < Δm < 172 MeV. σB refers to the product of the cross section and branching ratio for each particular mode for the Λ_c^+.

Λ_c^+ Decay mode	Events	Background	Signal[a]	$\sigma B/\sigma$(charge current)
$\Lambda\pi^+$	8	1.5	17.6	$(1.8 \pm 0.8) \times 10^{-4}$
$\bar{K}^0p$	7	2.0	25.5	$(2.7 \pm 1.6) \times 10^{-4}$
$\Lambda\pi^+\pi^+\pi^-$ ($Y^{*+}\pi^+\pi^-$)	4	1.5	12.4	$(1.5 \pm 1.4) \times 10^{-4}$
$\bar{K}^0p\pi^+\pi^-$ ($K^{*-}p\pi^+$)	1	1.0	⋯	⋯
Sum	20	6.0	55.5	$(6 \pm 2.3) \times 10^{-4}$

[a]Number of events (Ref. 9) above background corrected for detection efficiencies and unseen neutral decays of the $\bar{K}^0$ and the Λ.

events with $\Lambda_c^+ \to \Lambda\pi^+$ since this sample has the smallest background. The values obtained are

$$m(\Lambda_c^+) = 2257 \pm 10 \text{ MeV},$$

$$m(\Sigma_c^{++}) - m(\Lambda_c^+) = 168 \pm 3 \text{ MeV}.$$

It is interesting to note that one of the 20 events is probably an example of quasielastic charmed-baryon production. Kinematics and track identification suggest that the reaction is $\nu_\mu \text{Ne} \to \mu^- \Lambda\pi^+\pi^+\pi^+\pi^-$ with no missing particles. The event thus has the $\Delta S = -\Delta Q$ signature of charm production. Examination of the masses then indicates that the event is another example of the reaction

$$\nu p \to \mu^- \Sigma_c^{++},\ \Sigma_c^{++} \to \Lambda_c^+\pi^+,$$
$$\Lambda_c^+ \to Y^{*+}\pi^+\pi^-,\ Y^{*+} \to \Lambda\pi^+.$$

Two of the three π^+'s in this event are overstopped as K^+ and the interpretation of the third positive track heavily favors π^+ over K^+ by geometrical reconstruction, ionization, and longitudinal-momentum balance. Transverse momentum is balanced to within 70 MeV/c. There is no visible evidence for stubs at the primary vertex or additional neutrals in the downstream 7 radiation lengths and 2.5 interaction lengths. The probability that this event is associated strange-particle production with a missing K_L has been calculated to be less than 3%. The two relevant masses are $m(\Lambda_c^+) = 2276 \pm 25$ MeV and $\Delta m = 163 \pm 5$ MeV.

In summary, we have presented evidence for the existence of both the Σ_c^{++} and Λ_c^+ baryons, a measurement of their masses, as well as the first observations of two-body decay modes of the Λ_c^+: $\Lambda_c^+ \to \Lambda\pi^+$ and, with less significance, $\Lambda_c^+ \to \overline{K}^0 p$.

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[8]The two BNL charmed-baryon events (Refs. 3 and 5) have a $Y^*(1385)$ and $K^*(892)$, respectively, in their Λ_c^+ decay products.

[9]Figures show all mass combinations. In Table I we have made correct ions for multiple combinations within an event for both the signal and the background.

Interpretation of *p-p* Dibaryon Resonances at 2140, 2260, and 2430 MeV

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Recent elastic *p-p* C_{LL} measurements and other *p-p* data indicate the existence of $^1D_2$, $^3F_3$, and $^1G_4$ resonances at energies of about 2140, 2260, and 2430 MeV, respectively. These resonances accurately correspond to nuclear-physics–type rotational levels of a virtual $pp\pi(2020)$ bound state.

In a recent paper,[1] Auer *et al.* reported the possible existence of $^1D_2$, $^3F_3$, and $^1G_4$ proton-proton dibaryon resonances at energies of approximately 2140, 2260, and 2430 MeV. These energies correspond to the positions of dips in the elastic C_{LL} spin-correlation data.[1] Other evidence for this *p-p* resonant structure is obtained from cross-section differences between parallel and antiparallel longitudinal ($\Delta\sigma_L$) and transverse ($\Delta\sigma_T$) total cross sections, and from Legendre expansions of