Resonant production of Λ_c^+ baryons in neutrino-nucleus interactions in a photographic emulsion

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A significant fraction, $0.58^{+0.17}_{-0.22}$, of the charmed Λ_c^+ baryons in neutrino interactions may be produced through the decays of Σ_c resonances. Three of four detected events involving Λ_c^+ production are interpreted as the production and decay of charmed $\Sigma_c^0(2450)$, $\Sigma_c^{++}(2450)$ and $\Sigma_c^{++}(2510)$ resonances by the $\Sigma_c \to \Lambda_c^+ \pi^\pm$ mechanism. The mean value of the mass difference between $\Sigma_c(2450)$ and Λ_c^+ is 162 ± 2 MeV/c^2.

The existence of charmed $\Sigma_c(2450)$ and $\Sigma_c(2510)$ baryons is not a reliably established experimental fact.[1] Charmed Σ_c resonances should decay[2,3] primarily by the strong interaction $\Sigma_c \to \Lambda_c^+ \pi$, with a small contribution from a radiative decay channel,[4] $<1\%$.

The data which we are reporting here on the production of charmed Λ_c^+ baryons through resonant Σ_c states were obtained in the E-564 experiment.[5] In that experiment, a cryogenically sensitive BR-2 nuclear emulsion in the working volume of the Fermilab 15-foot bubble chamber was bombarded in a neutrino beam with a wide energy spectrum ranging up to 220 GeV. The analysis of each of the detected decays of charmed Λ_c^+ baryons was described in Refs. 6. Three of four events with the decays of Λ_c^+ baryons were consistent with the interpretation as the possible production and decay of $\Sigma_c^0(2450)$, $\Sigma_c^{++}(2450)$, and $\Sigma_c^{++}(2510)$ resonances into $\Lambda_c^+\pi^\pm$.

DECAYS OF CHARMED BARYONS

The decay modes and characteristics of the charmed baryons detected are listed in Table I. The lifetimes, $\tau_{\Lambda_c^+} = (2.1^{+1.5}_{-0.8}) \times 10^{-13}$ s, and masses, $M_{\Lambda_c^+} = 2287 \pm 13$ MeV/c^2, found experimentally for the charmed Λ_c^+ baryon agree well with the average data from other experiments.[1]

TABLE I. Characteristics of the decay of charmed baryons.

No.	Decay mode	Range before decay (μm)	Momentum (GeV/c)	Transit time before decay (10^{-13} s)	Mass (MeV/c^2)	Mass difference (MeV/c^2)
1	Σ_c^0 (2450) $\rightarrow \Lambda_c^+ \pi^-$		4.1			163 ± 2
	$\Lambda_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-$	154	3.7	3.13 ± 0.02	2300 ± 25	
2	Σ_c^{++}(2450) $\rightarrow \Lambda_c^+ \pi^+$		6.4			160 ± 3
	$\Lambda_c^+ \rightarrow pK^- \pi^+$	147	5.9	1.90 ± 0.07	2278 ± 40	
3	Σ_c^{++} (2510) $\rightarrow \Lambda_c^+ \pi^+$		28.4			235 ± 14
	$\Lambda_c^+ \rightarrow nK^- \pi^+ \pi^+$	1150	24.1	3.64 ± 0.35	2351 ± 116	
4	$\Lambda_c^+ \rightarrow pK^- \pi^+$	2.1	3.8	0.04 ± 0.01	2283 ± 15	–

In order to search for resonant Σ_c states in interactions involving the production of Λ_c^+ baryons, we calculated the effective masses of Λ_c^+ baryons with $\pi^\pm$ mesons identified in the events ($M_{\Lambda_c^+ \pi^\pm}$), with a mass difference $\Delta m = M_{\Lambda_c^+ \pi^\pm} - M_{\Lambda_c^+}$. Figure 1 is an ideogram of the values of[12)] Δm.

Each mass difference Δm, with an error $\sigma_{\Delta m}$, is represented on the ideogram by a rectangle with a base $2\sigma_{\Delta m}$ and a height $1/2\sigma_{\Delta m}$. The area of each of the rectangles corresponds to the area of the hatched square shown at the upper right in this figure. This ideogram gives an idea of the distribution of the mass difference Δm when the measurement errors are taken into account; such a representation is particularly important when these errors differ substantially. For a search for Σ_c states, a study of the mass difference $M_{\Lambda_c^+ \pi^\pm}$ and $M_{\Lambda_c^+}$ is preferable to a study of the absolute values of the mass $M_{\Lambda_c^+ \pi^\pm}$. Because of the correlation in the errors in the masses $M_{\Lambda_c^+ \pi^\pm}$ and $M_{\Lambda_c^+}$, the absolute error in the mass difference is smaller than the error in the mass $M_{\Lambda_c^+ \pi^\pm}$.

Theoretical values of 159–166 MeV/c^2 have been predicted[2,3] for the mass difference between baryon states from the triplet Σ_c (2450) and the Λ_c^+ baryon. Differences of 220–229 MeV/c^2 have been predicted between the baryon states from the triplet Σ_c (2510) and the Λ_c^+ baryon. The Σ_c (2450) and Σ_c (2510) widths calculated in Refs. 2 and 4 are ~5 and ~20 MeV, respectively. In region I in Fig. 1, which corresponds to the theoretically expected difference between the Σ_c (2450) and Λ_c^+ masses, we see two good measurements of the mass difference Δm from events 1 and 2. The other values lie much further on along the Δm scale. There are a few pieces of experimental evidence[3] (nine events) which also indicate a value $\Delta m \sim$ 159–177 MeV/c^2 for the mass difference between Σ_c (2450) and Λ_c^+. Event 1 is interpreted as the decay $\Sigma_c^0(2450) \rightarrow \Lambda_c^+ \pi^-$ with a mass difference 163 ± 2 MeV/c^2, and event 2 as the decay

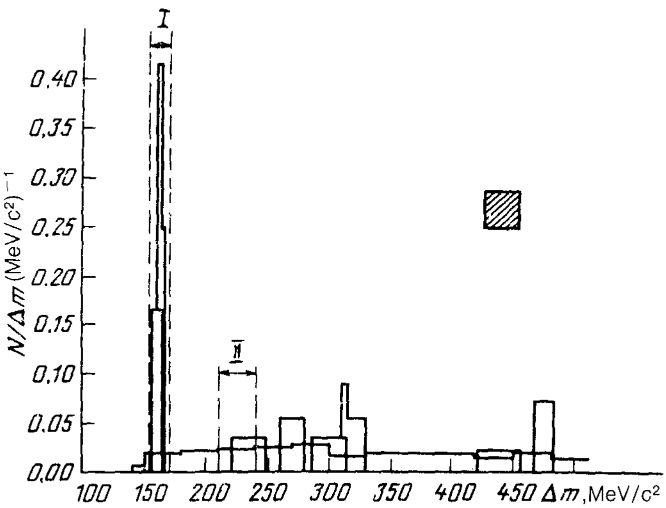

FIG. 1. Ideogram for the mass difference $\Delta m = M_{\Lambda_c^+ \pi^\pm} - M_{\Lambda_c^+}$. The number of events in an interval of 1 MeV/c^2 is plotted along the ordinate. Regions I (156–169 MeV/c^2) and II (210–239 MeV/c^2) correspond to the theoretical predictions of the mass differences $M_{\Sigma_c(2450)} - M_{\Lambda_c^+}$ and $M_{\Sigma_c(2510)} - M_{\Lambda_c^+}$, respectively, where the widths of the Σ_c resonances have been taken into account. The hatched square corresponds to one event.

$\Sigma_c^{++}(2450) \to \Lambda_c^+ \pi^+$, with a mass difference 160 ± 3 MeV/c^2. In region II in Fig. 1 there is an indication of a decay $\Sigma_c^{++}(2510) \to \Lambda_c^+ \pi^+$ with $\Delta m = 235 \pm 14$ MeV/c^2 (event 3). The background for the decays $\Sigma_c \to \Lambda_c^+ \pi^\pm$ was calculated from the number of events expected in region I (156–169 MeV/c^2) and region II (210–239 MeV/c^2) according to the mass differences between the Σ_c and Λ_c^+ baryons. To estimate the expected number of events in regions I and II, we calculated the Δm distribution for Λ_c^+ baryons with shower particles (under the assumption that these particles are π mesons) from the neutrino interactions found experimentally. In this calculation we selected events with an invariant mass (W) of the hadron system which corresponded to the mean value of W in events with Λ_c^+ production. The resulting distribution was normalized over the mass-difference interval 250 MeV/$c^2 \leqslant \Delta m \leqslant 500$ MeV/c^2 to the corresponding distribution for four events with the production of Λ_c^+ baryons (Fig. 1) and extrapolated to the region $\Delta m < 250$ MeV/c^2. The normalized distribution is shown by the solid stepped line in this figure. An estimate of the number of events expected in the region of the difference between the masses of the Σ_c and Λ_c^+ baryons leads to the following background level: 0.41 ± 0.19 for $\Sigma_c^{++}(2510)$, 0.13 ± 0.06 for $\Sigma_c^{++}(2450)$, and 0.10 ± 0.04 event for $\Sigma_c^0(2450)$. The total background is 0.7 ± 0.2 event.

The average mass[13)] found for the $\Sigma_c(2450)$ states over the two detected events is 2455 ± 22 MeV/c^2; the mass difference is $\Sigma_c(2450)$ and $\Lambda_c^+ - 162 \pm 2$ MeV/c^2.

Using these figures we can estimate the relation between the direct production of Λ_c^+ and the production through Σ_c resonances:

$$R_{\Lambda_c^+} = \frac{\Sigma_c \to \Lambda_c^+ \pi^\pm}{\text{All } \Lambda_c^+} = 0.58^{+0.17}_{-0.22}$$

This result indicates that a significant fraction of the Λ_c^+ baryons may be produced through Σ_c resonances in neutrino interactions. Theoretical estimates[2,3] of the value of $R_{\Lambda_c^+}$, ignoring the particular features of the dynamics of the production of charmed baryons, yield a value of 0.6 for $R_{\Lambda_c^+}$. We see that the theoretical value agrees with the result of the present experiment. This agreement indicates that the dynamics of the production of charmed baryons apparently does not substantially disrupt the relation between the relative production of Λ_c^+ and Σ_c baryons as estimated exclusively on the basis of charge independence and spin statistics.

We should point out in conclusion that the neutrino interactions involving the production of charmed baryons which were detected in our experiment differ substantially in terms of the magnitude of the square 4-momentum transfer Q^2 from events involving the production of charmed D mesons. The mean value of Q^2 in interactions involving the production of charmed baryons is ~ 4 $(\text{GeV/c})^2$, while that in events with D mesons is $\langle Q^2 \rangle \sim 19$ $(\text{GeV/c})^2$. In the parton model, the production of charmed baryons is most probable in the coalescence of partons of the nucleon core and the c quark produced. As a result, there is a limitation[8] on Q^2 $(Q^2 < M^2_{\Lambda_c^+})$, as observed in the experiment.

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12) Several values of Δm, which lay in the interval $\sim$1–2 GeV/c^2, were excluded from further analysis.
13) The mass difference within the Σ_c multiplets has been estimated in several papers[7]; the mean value is on the order of a few MeV.

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