Nuclear-emulsion observation of the decay of a charmed Σ_c^0 baryon into $\Lambda_c^+\pi^-$ followed by a Λ_c^+ decay into $\Sigma^+\pi^-\pi^+$

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An event in which the decay of a charmed Σ_c^0 baryon into Λ_c^+ and π^- has been detected in a neutrino experiment with a nuclear emulsion is described. The decay of the Λ_c^+ baryon occurs in the channel $\Lambda_c^+\to\Sigma^+\pi^-\pi^+$ with an observable subsequent decay of $\Sigma^+\to\pi^+n$. The mass of the Λ_c^+ is 2.300 ± 0.025 GeV/c^2, and it decays in a time of $(3.13\pm0.02)\times10^{-13}$ s. The mass of the Σ_c^0 baryon and the difference between the Σ_c^0 and Λ_c^+ masses are 2.462 ± 0.026 GeV/c^2 and 0.163 ± 0.002 GeV/c^2, respectively.

This letter reports an analysis of one of the decays of short-lived particles which was detected in the experiment of Ref. 1 with a nuclear emulsion in the active volume of a 15–foot bubble chamber. The emulsion was exposed in a broad-band neutrino beam at the accelerator at the Fermi National Accelerator Laboratory. The decay described below was found in one of the ~150 neutrino interactions which go through a charged current and which have already been detected (the muon in the event is identified kinematically[2]). Other decays of short-lived particles found in this experiment and the experiment itself are described elsewhere.[1,3]

Decay of a charged particle over a distance of 154 μm. The event in the emulsion is shown schematicaly in Fig. 1. Relativistic track 1, from the primary vertex A, forms a secondary vertex B of three relativistic tracks: 11, 12, and 13. Two of these tracks (12 and 13) emerge from the emulsion into the bubble chamber. On track 11, at a point ~1.6 cm from vertex B, in the emulsion, we see a change in direction of ~26° (vertex C). After this change in direction of track 11, the continuation of this track, which we call track 111, goes into the bubble chamber. For all the tracks that emerge from the emulsion into the bubble chamber we determined the momenta and the signs of the charges of the corresponding particles from measurements on the photographs. In determining the momenta we allowed for the ionization loss in the emusion and in the wall of the emulsion container. Table I lists information on the tracks pertaining to vertices B and C.

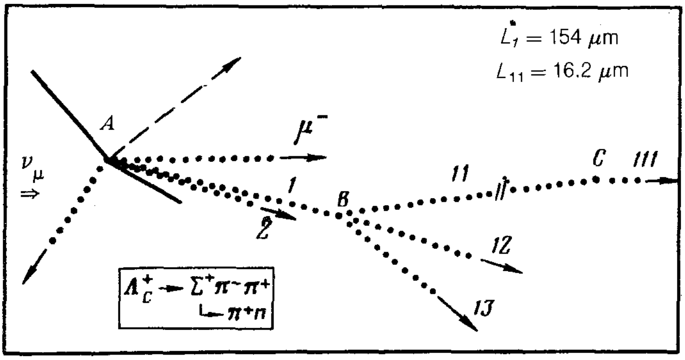

FIG. 1. Schematic diagram of the event in the emulsion.

That component of the resultant momentum of particles 12 and 13 which is normal to the plane defined by tracks 1 and 11 is 0.002 ± 0.019 GeV/c. Since the vectors of particles 1 and 11 are coplanar with the resultant momentum of particles 12 and 13, we can conclude that no neutral particles are present among the products of the presumed decay of particle 1.

Working from the kinematic balance equations for the momenta of the four particles at vertex B, we estimate the momentum of particle 11 (a 1-C fit with $\chi^2 = 0.02$) to be 1.77 ± 0.05 GeV/c. To identify particles 11 and 111, we measured the ionization on their tracks in the same emulsion layers. Using the ionization-ratio method,[3] we unambiguously identified these particles as a Σ^+ hyperon and a π^+ meson (the measured ratio of the ionizations on these tracks, $g_{11}/g_{111} = 1.15 \pm 0.03$, agrees well with the ratio which would be expected on the basis of the ionization curves, $g^*_\Sigma/g^*_\pi = 1.17 \pm 0.02$, while the ratio for the closest alternative hypothesis, the p, π hypothesis, for particles 11 and 111 would be $g^*_p/g^*_\pi = 1.07 \pm 0.01$. In the identification of particle 11 as a Σ^+, the estimate of the value of $P\beta$ on the basis of the scattering in the emulsion for the particle agrees with the momentum found for it from the kinematic balance equations for the momenta at vertex B. The probable interpretation of the change in direction on track 11 is the hypothesis of the decay $\Sigma^+ \to \pi^+ n$. The momentum of the pion estimated from the kinematics of this decay should be 0.417 ± 0.004 GeV/c, in agreement with the momentum measured for particle 111 in the bubble chamber (0.429 ± 0.017 GeV/c). The time that elapses before the decay of the Σ^+ hyperon detected here is $\sim 0.4 \times 10^{-10}$ s. The tabulated value[4] of the lifetime of the Σ^+ hyperon is $(0.800 \pm 0.004) \times 10^{-10}$ s.

To identify particles 12 and 13, we continued their tracks and also the track of the negatively charged particle, which does not interact in the bubble chamber and which emerges from the primary vertex with a momentum of 54 GeV/c (the track of a μ^- meson), in two emulsion layers. On the basis of ionization measurements, we unambiguously identified the negatively charged particle 12 as a pion, while positively charged particle 13 might be identified as a pion or a kaon.

The set of identified secondary particles at vertex B indicates the decay of a charmed Λ_c^+ baryon:

TABLE I. Characteristics of the tracks at the vertices of the decays.

Vertex	Track	Measurements in emulsion			Measurements in bubble chamber			Mass hypotheses	(predicted-measured)	
		Azimuthal angle φ°	Immersion angle λ°	$P\beta$ (GeV)/c)	Momentum (GeV/c)	Charge	Characteristic of track[1)]		$\Delta\varphi^\circ$	$\Delta\lambda^\circ$
B	1	-16.30 ± 0.00	3.97 ± 0.25							
	11	4.00 ± 0.07	12.01 ± 0.22	1.1 ± 0.5	$1.77 \pm .05$ [2)]			Σ		
	12	-20.91 ± 0.05	-4.67 ± 0.22		$1.12 \pm .04$	$-$	Int	π	$1,2 \pm 0,9$	$-0,4 \pm 0,9$
	13	-41.89 ± 0.09	-0.51 ± 0.24		$1.18 \pm .04$	+	Em	π, K	$0,3 \pm 1,1$	$2,1 \pm 1,4$
C	11	4.00 ± 0.00	12.84 ± 0.23							
	111	-1.65 ± 0.04	-12.78 ± 0.19		$0.43 \pm .02$	+	Int	π	$0,7 \pm 1,9$	$-0,3 \pm 1,9$

1) Int—The particle interacts in the bubble chamber; Em—the particle escapes from the bubble chamber without interacting.

2) The momentum of this particle was estimated from the transverse-momentum balance at vertex B.

TABLE II. Interpretation of the vertices in the decay and the primary vertex.

Interpretation of decay	Angle with ν beam.	Decay length (μm)	Momentum (GeV/c)	Lifetime (10^{13} s)	Primary vertex[1]	E (GeV)	x	y
						Apparent values[2]		
$\Sigma_c^{\circ} \to \Lambda_c^{+}\pi^{-}$	15.3°		4.1		$\nu A \to \mu^{-}\Sigma_c^{\circ}\pi p 2b(X^{\circ})A'$	59.2	0.13	0.08
$\Lambda_c^{+} \to \Sigma^{+}\pi^{-}\pi^{+}$	14.3°	154	3.7	3.13 ± 0.02	$\to \Lambda_c^{+}\pi^{-}$			

[1] b represents evaporation particles.

[2] The apparent energy of the neutrino is found as the projection of the resultant momentum of the secondary particles onto the direction of the neutrino beam; x and y are the standard scaling variables.

$$\Lambda_c^+ \to \Sigma^+ \pi^- \pi^+ .$$

A kinematic two-vertex 2-C fit (with $\chi^2 = 0.53$) yields the following value for the mass of the Λ_c^+ baryon that has decayed:

$$M = 2.300 \pm 0.025 \text{ GeV}/c^2.$$

This value agrees well with the tabulated mass of Λ_c^+. The momentum found for the Λ_c^+ by a kinematic 3-C fit (with $\chi^2 = 1.02$) is 3.744 ± 0.013 GeV/c. At this momentum, a range of 154 ± 0.5 μm corresponds to the following decay time:

$$\tau = (3.13 \pm 0.02)\times 10^{-13} \text{ s} .$$

This value agrees well with the tabulated lifetime of the Λ_c^+. The literature reveals no previous data on the decay of a charmed Λ_c^+ into Σ^+,π^-, and π^+.

Cascade decay of a charmed Σ_c^0 baryon. At the primary vertex there is a relativistic track of the event (track 2 in Fig. 1). This track, which runs at an angle $\sim 15°$ from the track of the Λ_c^+ baryon, belongs to a negatively charged particle, with a momentum 0.319 ± 0.11 GeV/c. This particle interacts in the bubble chamber. On the basis of ionization measurements in the emulsion, we unambiguously identified this particle as a π^- meson. The effective mass of the pair consisting of the pion and the Λ_c^+ baryon is

$$M_{\pi\Lambda} = 2.462 \pm 0.026 \text{ GeV}/c^2.$$

The difference between this mass and the Λ_c^+ mass is

$$\Delta M = 0.163 \pm 0.002 \text{ GeV}/c^2.$$

These values are close to the expected values of M and ΔM for the charmed particle[5] Σ_c (2450); experimental evidence for the existence of this particle has been found in several studies.[4]

In summary, the event detected by us can be interpreted as the following cascade decay of a charmed Σ_c^0 baryon after it is produced in a neutrino interaction which goes through a charged current:

$$\Sigma_c^0 \to \Lambda_c^+ \pi^-$$
$$\quad\quad \hookrightarrow \Sigma^+ \pi^- \pi^+$$
$$\quad\quad\quad\quad \hookrightarrow \pi^+ n .$$

Table II gives the probable interpretation of the vertex of the primary neutrino interaction and its kinematic characteristics.

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