ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT

Physics Letters B 555 (2003) 156–166

PHYSICS LETTERS B

www.elsevier.com/locate/npe

Measurement of Λ_c^+ production in neutrino charged-current interactions

CHORUS Collaboration

A. Kayis-Topaksu, G. Onengüt

Çukurova University, Adana, Turkey

R. van Dantzig, M. de Jong, O. Melzer, R.G.C. Oldeman [1], E. Pesen, F.R. Spada [2], J.L. Visschers

NIKHEF, Amsterdam, The Netherlands

M. Güler [3], U. Köse, M. Serin-Zeyrek, R. Sever, P. Tolun, M.T. Zeyrek

METU, Ankara, Turkey

N. Armenise, M.G. Catanesi, M. De Serio, M. Ieva, M.T. Muciaccia, E. Radicioni, S. Simone

Università di Bari and INFN, Bari, Italy

A. Bülte, K. Winter

Humboldt Universität, Berlin, Germany [4]

R. El-Aidi, B. Van de Vyver [5,6], P. Vilain [7], G. Wilquet [7]

Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium

B. Saitta

Università di Cagliari and INFN, Cagliari, Italy

E. Di Capua

Università di Ferrara and INFN, Ferrara, Italy

S. Ogawa, H. Shibuya

Toho University, Funabashi, Japan

0370-2693/03/$ – see front matter
doi:10.1016/S0370-2693(03)00045-5

A. Artamonov [8], M. Chizhov [9], M. Doucet [10], I.R. Hristova [9], T. Kawamura, D. Kolev [9], H. Meinhard, J. Panman, I.M. Papadopoulos, S. Ricciardi [11], A. Rozanov [12], R. Tsenov [9], J.W.E. Uiterwijk, P. Zucchelli [13]

CERN, Geneva, Switzerland

J. Goldberg

Technion, Haifa, Israel

M. Chikawa

Kinki University, Higashiosaka, Japan

E. Arik

Bogazici University, Istanbul, Turkey

J.S. Song, C.S. Yoon

Gyeongsang National University, Jinju, South Korea

K. Kodama, N. Ushida

Aichi University of Education, Kariya, Japan

S. Aoki, T. Hara

Kobe University, Kobe, Japan

T. Delbar, D. Favart, G. Grégoire, S. Kalinin, I. Makliouevа

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

P. Gorbunov [6], V. Khovansky, V. Shamanov, I. Tsukerman

Institute for Theoretical and Experimental Physics, Moscow, Russia

N. Bruski, D. Frekers

Westfälische Wilhelms-Universität, Münster, Germany [3]

K. Hoshino, J. Kawada, M. Komatsu, M. Miyanishi, M. Nakamura, T. Nakano, K. Narita, K. Niu, K. Niwa, N. Nonaka, O. Sato, T. Toshito

Nagoya University, Nagoya, Japan

S. Buontempo, A.G. Cocco, N. D'Ambrosio, G. De Lellis, G. De Rosa, F. Di Capua, A. Ereditato, G. Fiorillo, A. Marotta, M. Messina, P. Migliozzi, C. Pistillo, L. Scotto Lavina, P. Strolin, V. Tioukov

Università Federico II and INFN, Naples, Italy

K. Nakamura, T. Okusawa

Osaka City University, Osaka, Japan

U. Dore, P.F. Loverre, L. Ludovici, P. Righini, G. Rosa, R. Santacesaria, A. Satta

Università La Sapienza and INFN, Rome, Italy

E. Barbuto, C. Bozza, G. Grella, G. Romano, C. Sirignano, S. Sorrentino

Università di Salerno and INFN, Salerno, Italy

Y. Sato, I. Tezuka

Utsunomiya University, Utsunomiya, Japan

Received 21 December 2002; accepted 9 January 2003

Editor: L. Montanet

Abstract

A measurement of Λ_c^+ production in neutrino nucleon charged-current interactions is presented. In a subsample of about 50 000 interactions located in the emulsion target of the CHORUS detector, exposed to the wide band neutrino beam of the CERN SPS, candidates for decays of short-lived particles were identified using new automatic scanning systems and later confirmed through visual inspection. Criteria based on the flight length allowed a statistical separation among the different charm species thus enabling a sample particularly rich in Λ_c^+ to be defined. At an average neutrino energy of 27 GeV, the product $\sigma(\Lambda_c^+)/\sigma(\mathrm{CC}) \times BR(\Lambda_c^+ \to 3p)$ was measured to be $(0.37 \pm 0.10(\mathrm{stat}) \pm 0.02(\mathrm{syst})) \times 10^{-2}$, while the values of $(1.54 \pm 0.35(\mathrm{stat}) \pm 0.18(\mathrm{syst})) \times 10^{-2}$ and of $0.24 \pm 0.07(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ were obtained for $\sigma(\Lambda_c^+)/\sigma(\mathrm{CC})$ and $BR(\Lambda_c^+ \to 3p)$, respectively.

E-mail address: jaap.panman@cern.ch (J. Panman).

[1] Now at University of Pennsylvania, Philadelphia, USA.

[2] And INFN, Roma, Italy.

[3] Now at Nagoya University, Nagoya, Japan.

[4] Supported by the German Bundesministerium für Bildung und Forschung under contract numbers 05 6BU11P and 05 7MS12P.

[5] Fonds voor Wetenschappelijk Onderzoek, Belgium.

[6] Now at CERN, 1211 Geneva 23, Switzerland.

[7] Fonds National de la Recherche Scientifique, Belgium.

[8] On leave of absence from ITEP, Moscow.

[9] On leave of absence from St. Kliment Ohridski University of Sofia, Bulgaria.

[10] Now at University of Maryland, MD, USA.

[11] Now at Royal Holloway College, University of London, Egham, UK.

[12] Now at CPPM CNRS-IN2P3, Marseille, France.

[13] On leave of absence from INFN, Ferrara, Italy.

1. Introduction

Charm production in neutrino charged-current (CC) interactions has been studied in several experiments, mainly by means of dimuon events and, in particular, by CDHS [1], CCFR [2], CHARM [3], CHARM-II [4], NOMAD [5] and NuTeV [6]. In events with two muons in the final state, the leading muon is interpreted as originating from the neutrino interaction vertex and the other as the product of the semileptonic decay of a charmed particle. In experiments of this type, the decay topology cannot be identified. In addition, to obtain the total charm production rate, the fractions of different charmed particles need to be known, as well as their muonic branching ratio. On the other hand, experiments like BEBC [7] and NOMAD [8] have identified specific charm production channels by exploiting their capabilities to measure accurately invariant mass.

Even though evidence for charmed baryon production by neutrinos has been reported in the literature with few events observed in a number of different bubble chamber experiments [9–13], cross-section values are still affected by large errors.

A measurement of charm production and of the fraction of charmed particles was obtained by E531 [14] at FNAL, an emulsion hybrid experiment in which decays of charmed particles were identified in the target emulsion on the basis of their topology. Statistics was limited however, the total sample of charged charm decays consisting of 62 events only.

The development of high speed, automatic emulsion scanning systems within CHORUS—an emulsion hybrid experiment as well—allows studies of charm production to be made with much higher statistics than achievable in the past by similar experiments.

In this Letter, results on Λ_c^+ production obtained from a sample of the CHORUS data are presented with measurements of the cross-section relative to CC interactions and of the topological branching ratio into three charged particles.

2. Experimental apparatus

CHORUS was designed to search for $\nu_\mu \to \nu_\tau$ oscillation through the detection of the characteristic topology of the τ-lepton decay in ν_τ CC events. The detector was a hybrid setup that combines a 770 kg nuclear emulsion target with various electronic detectors [15]. The nuclear emulsion is used as target for neutrino interactions, allowing three-dimensional reconstruction of short-lived particles. The emulsion target was segmented into four stacks, each divided into eight modules. The basic element of a module is a *plate*, two 350 µm layers of emulsion on either side of a 90 µm plastic base of size 36×72 cm^2; 36 plates form a module. Each stack is followed by three interface emulsion sheets with a 90 µm emulsion layer on both sides of a 800 µm thick plastic base—which yields an angular resolution of the order of 1 mrad—and by a set of scintillating fibre trackers which provide an accurate prediction of particle trajectories into the emulsion stack for the location of the neutrino interaction vertex. The accuracy of the fibre tracker prediction is about 150 µm in position and 2 mrad in angle.

The CHORUS detector was exposed to the wide band neutrino beam (average energy 27 GeV) of the CERN SPS during the years 1994–1997, with an integrated flux of 5.06×10^{19} protons on target. The beam consists mainly of ν_μ with a contamination of 6% $\bar{\nu}_\mu$ and $\sim 1\%$ of ν_e. The original search was optimised to detect muonic decays of the τ lepton and therefore it excluded events in which the muon had a momentum larger than 30 GeV/c. This selection is no longer applied for charm production studies. For ν_μ CC interactions the muon track, reconstructed by the scintillating fibre system, was searched for in the interface emulsion. If found, it was followed upstream by means of an automatic scanning system [16] until no longer found in the target emulsion, thus indicating the existence of a possible vertex.

In total about 150 000 ν_μ CC events have been located in emulsion so far as a result of this procedure. Within a volume of 1.5 mm × 1.5 mm × 6.3 mm around the position where the μ^- track disappeared, a new automatic scanning system, called 'Ultra Track Selector' (UTS) [17], is used to record the spatial coordinates of points along the trajectories of all charged particles that have an angle of less than 400 mrad with respect to the incident neutrino direction, with a detection efficiency of more than 98%. In what follows, this procedure will be referred to as 'NetScan' [18].

The reconstruction of charged-particle trajectories in the NetScan volume allows a search for the decays of short-lived particles to be performed. The results presented in this Letter are based on a sample of about 50 000 ν_μ CC events analysed with the NetScan method.

3. Event samples and selection of decay topologies

Since it is not possible to identify decays on an event-by-event basis, the separation among the different charmed particles is achieved in a statistical manner by exploiting their different lifetimes and hence flight-length distributions. Therefore, the NetScan data, after reconstruction, are analysed by applying two different sets of criteria. The aim is to select one sample enriched in Λ_c^+ decays (selection A) and another where D^+ and D_s^+ decays should dominate (selection B).

Both selections require that the primary muon track be detected in more than two emulsion plates and that its direction match with that measured in the fibre tracker system. The plate in which the muon track originates is assumed to be the neutrino interaction vertex plate.

Selection A aims to detect mostly decays occurring in the same emulsion plate as the vertex. It requires that the minimum distance between the muon track and any other track—provided that it originates in the same plate and is detected in at least three plates—be more than 5 µm and less than 30 µm. This would select decays with a topology of the type sketched in Fig. 1.

Selection B aims to detect decays occurring in plates downstream of the vertex plate and proceeds as follows.

- Define as primary those tracks that have their origin in the vertex plate, are measured in at least one emulsion plate and with minimum distance from the muon less than 5 µm.
- Select, among the primary tracks, those that 'stop' (i.e., are not found along the straight line extrapolation of their original direction) within the NetScan volume, thus identifying a possible secondary vertex plate.
- Require that the minimum distance between the 'stopping' track and at least one other track originating in the secondary vertex plate is less than 5 µm.

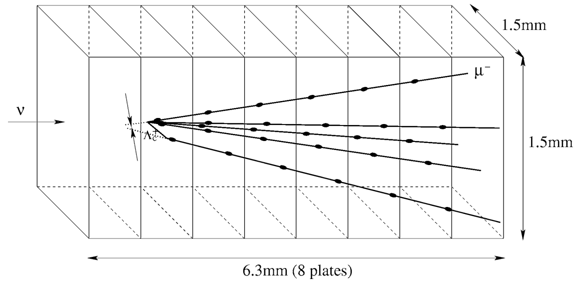

Fig. 1. Schematic view of typical decays selected by criterion A. The ellipses represent the points measured by the UTS at each emulsion sheet interface.

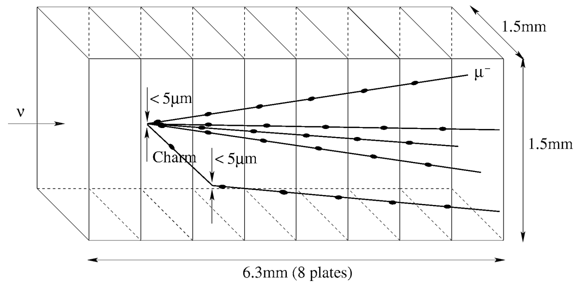

Fig. 2. Schematic view of decay topologies selected by criterion B.

These criteria would select decays of topology shown in Fig. 2.

Both selections are used to define samples of events to be visually inspected at a later stage for the presence of a decay. A secondary vertex is accepted as decay if the number of charged products is consistent with charge conservation and no other activity (nuclear or Auger electron) is observed.

Decays into a single charged particle (C1) are accepted only if the angle between the parent and the decay product *kink* angle) is greater than 50 mrad. The distance between the primary and decay vertices measures the flight length.

The criteria specified by selection A were applied to a sample of 50 414 μ events (5157 of which had a muon with momentum greater that 30 GeV/c) and 1614 events were selected for visual inspection. The observed decay topologies are shown in Table 1, while details on the rejected events are given in Table 2. This latter sample consists mainly of low-momentum tracks ($\sim$ 43%) that appear to have a large impact parameter owing to multiple Coulomb scattering and of tracks traversing the plate ($\sim$ 41%) on which

Table 1
Results of visual inspection for candidates accepted as decays. C and N indicate charged and neutral particles, respectively; the digit represents the number of charged decay products

Decay type	Selection A	Selection B
C1	70	165
C3	84	103
C5	3	5
N2	118	–
N4	32	–
Total	307	273

Table 2
Classification of candidates rejected as possible decays

Type	Selection A	Selection B
Low momentum	566	41
Traversing tracks	542	122
Nuclear fragment	105	37
γ-conversion	46	6
Hadron interactions	29	97
Reconstruction failure	19	10
Total	1307	313

the reconstruction program failed, again because of multiple Coulomb scattering. The remainder consists of nuclear fragments from the neutrino interaction vertex, gamma conversion, hadronic interactions, and fake tracks due to the failure of the reconstruction program.

The criteria specified by selection B were applied to 56 761 ν_μ CC interactions (5061 of which have $p_\mu > 30$ GeV) and identified 586 events as possible decay candidates. The results of their visual inspection are summarised in Tables 1 and 2.

There is a loss of efficiency for decays that occur close either to the main interaction vertex or to the most downstream edge of the NetScan volume. To ensure a high efficiency of the visual inspection, flight lengths of 40–400 µm and 400–2400 µm were required for the samples selected with criteria A and B, respectively.

The number of surviving events is shown in Table 3, separately for decays into a single or three charged particles since, as will be shown later, background sources contribute different amounts to the different topologies. Decays into five charged particles are not used in the analysis, and their contribution will be

Table 3
Number of candidates after the selection on flight length

	Selection A $40\ \mu m < FL < 400\ \mu m$		Selection B $400\ \mu m < FL < 2400\ \mu m$	
	observed	corrected	observed	corrected
C1	62	84.8	133	195.0
C3	66	81.2	77	86.3
Total	128	166.0	210	281.3

accounted for by applying a correction. The location of events with $p_\mu > 30\ \mathrm{GeV}/c$ is in progress and selections A and B have been applied not to the complete but to samples of different size. To account for the difference, since within CHORUS the ratio of ν_μ CC events with $p_\mu > 30\ \mathrm{GeV}/c$ to $p_\mu < 30\ \mathrm{GeV}/c$ has been measured to be 0.381 ± 0.001, a weight has been applied to the analysed events with $p_\mu > 30\ \mathrm{GeV}/c$ in such manner that the ratio to those with $p_\mu < 30\ \mathrm{GeV}/c$ coincides with the one that has been measured on the total sample. This weight factor is 3.53 and 4.10 for events of samples A and B, respectively. The number of events obtained with the weighting procedure is also given in Table 3.

Fig. 3 shows the flight-length distributions for decays into three charged particles for events in the two regions, compared with the expected distributions for the charged charm mesons D^+ and D_s^+, obtained with the simulation described in Section 4 and normalised to the observed number of events.

A difference in shape and an excess of events is visible in the region of small flight lengths (below 200 µm) for selection A and it constitutes evidence for Λ_c^+ decays.

To corroborate this statement, the decay products of the charm candidates selected with criterion A were followed farther downstream in the NetScan volume. The aim was to search for possible decays at distances of several centimeters from the charm decay vertex, which would be evidence for the decay chain $\Lambda_c^+ \to \Sigma^\pm$, since no decay products of charm other than Σ's would decay with flight lengths of this order. Twelve such secondary decays were observed, six in which the decay occurred in the target emulsion and six in which it took place in the space between the target and interface emulsions. A detailed analysis of these events is in progress and would allow a determination of the decay branching ratio $\Lambda_c^+ \to \Sigma^\pm$. In the context

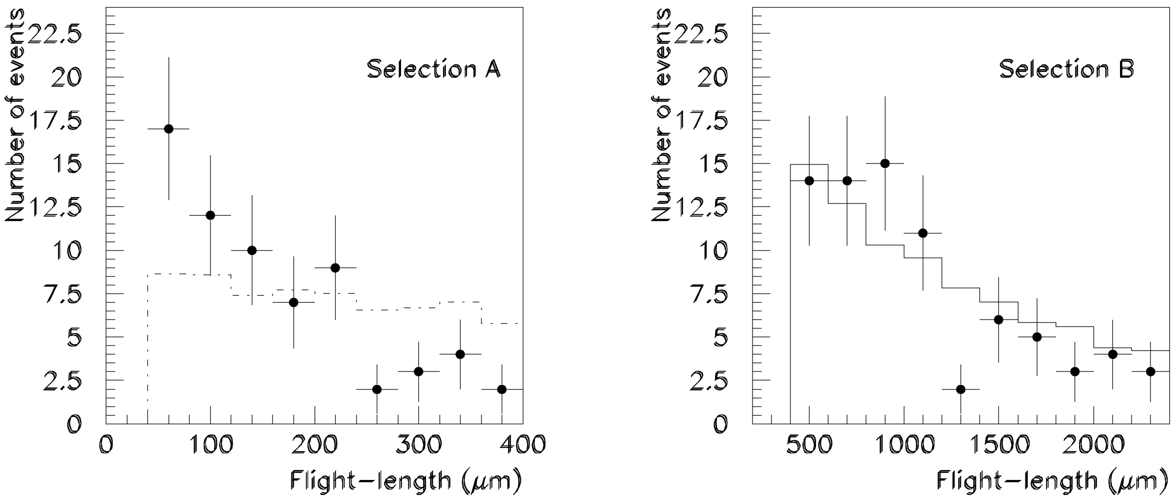

Fig. 3. Flight-length distributions of charged charm candidates decaying into three particles. The histograms represent the flight-length distributions given by the Monte Carlo simulation for D^+ and D_s^+, normalised to the number of observed events.

of this Letter, however, since preliminary estimations indicate that the background is less than one event, they should simply be considered as further evidence of Λ_c^+ in the sample selected with criterion A.

4. Efficiency evaluation

Detection efficiencies were evaluated with a GEANT3 [19] based Monte Carlo simulation of the experiment. Large samples of deep-inelastic neutrino interactions were generated according to the beam spectrum using a generator (JETTA [20]) derived from LEPTO [21] and JETSET [22]. Quasi-elastic (QE) reactions and resonance production were generated with the RESQUE [23] package with a rate of 9.6% relative to deep-inelastic scattering reactions. Quasi-elastic processes resulting in Λ_c^+ production were also simulated using the differential cross-sections of Ref. [24]. The simulated response of the CHORUS electronic detectors is processed through the same reconstruction program used for the data analysis.

The efficiency of the event location procedure was estimated as a function of the muon momentum using real data. Since the muon momentum spectrum of all charged current interactions is different from that in which charmed hadrons are produced, the ratios of reconstruction and location efficiency for events with a specific charmed hadron in the final state to that of all ν_μ CC events was estimated using the muon momentum spectrum given by Monte Carlo simulation. They were found to be 0.99 ± 0.01 for Λ_c^+, produced in deep-inelastic processes, 1.24 ± 0.01 for Λ_c^+ produced in quasi-elastic processes (including Σ_c^+ and Σ_c^{++}), 0.90 ± 0.01 for D^+, and 0.89 ± 0.01 for D_s^+.

To evaluate the NetScan efficiency, the emulsion data of the simulated events were merged with real NetScan data where the volume did not contain any event but only tracks which stop or pass through the volume, thus representing realistic background conditions. The performance of the UTS was also simulated using data accumulated in the NetScan procedure.

This method allows estimates of efficiencies for the processes of interest in the two regions (A and B) and for the decay topologies (1-prong, 3-prong) used for the analysis. The efficiencies (ε_{A1}, ε_{A3}, ε_{B1}, ε_{B3}) are shown in Table 4. They are a function of the decay topology and have only a mild dependence upon the region considered. Included in the same table are also the values of the geometrical acceptances in the two regions, which essentially take into account the different decay length and therefore momentum spectra of charmed hadrons. For Λ_c^+ decays the results are quoted separately for quasi-elastic and deep-inelastic processes since the momentum spectrum is quite different in the two cases and the ratio at production is not known. The figures in the table include also the loca-

Table 4
Geometrical acceptance and efficiency for decays of charmed hadrons

	Λ_c^+	Λ_c^+ (QE)	D^+	D_s^+
A_A	0.573 ± 0.010	0.584 ± 0.005	0.171 ± 0.005	0.280 ± 0.008
ε_{A1}	0.145 ± 0.015	0.104 ± 0.007	0.187 ± 0.017	0.166 ± 0.020
ε_{A3}	0.437 ± 0.018	0.341 ± 0.010	0.363 ± 0.018	0.429 ± 0.022
A_B	0.193 ± 0.008	0.019 ± 0.001	0.446 ± 0.006	0.508 ± 0.009
ε_{B1}	0.226 ± 0.028	0.070 ± 0.052	0.253 ± 0.012	0.252 ± 0.018
ε_{B3}	0.269 ± 0.028	0.261 ± 0.052	0.407 ± 0.012	0.339 ± 0.016

tion and reconstruction efficiencies mentioned above. The errors are those due to the statistical uncertainties in the simulation.

5. Background evaluation

Sources of background affect differently the two regions chosen for the analysis and furthermore their contribution is topology dependent.

The background from the decay of strange particles has been evaluated using the Monte Carlo simulation described in Section 4. The only sizeable contribution is from $\Sigma^\pm$ decays and amounts to 7.2 ± 2.3 events for the sample defined by selection B and decays of type C1, while it is negligible for the sample of selection A. Negligible as well is the contribution from $K^\pm$ decays into one or three particles for both selections.

Interactions yielding one or three hadrons in the final state and without any *activity* at the vertex that might indicate nuclear breakup, constitute the main source of background to charged charm decays. However—as is evaluated in what follows—hadronic interactions practically contribute only to C1 decays, leading to the background commonly known as *white kink* because of its topology. Simulations using FLUKA [25] have been carried out and the interaction lengths of various processes (including those without activity at the vertex) have been obtained. On the other hand, a number of interactions in emulsion has been collected by CHORUS in the search for neutrino oscillations and in studies of charm decays. This allows experimental cross checks of the calculations, albeit with large errors given the limited statistics.

For the process with three charged hadrons in the final state and having no nuclear activity, an interaction length of ~ 66 m, averaged over the momentum spectrum of pions produced in νN CC interactions, is obtained in the Monte Carlo simulation [26]. This, taking into account the number of hadrons produced and assuming a detection efficiency equal to that for charm decays, would yield a background of the order of one event for the C3 sample of selection B.

Quite different is the situation for decays into one charged particle only, for which the computed interaction length is ~ 2.5 m and therefore the background significantly larger.[14]

To check the contamination from this background, p_T, the momentum of the particle beyond the kink transverse to the direction of flight of the parent, is measured using the position displacements along the trajectory caused by multiple Coulomb scattering in the target emulsion. The p_T distributions are shown in Fig. 4 separately for the two regions A and B, for events for which the measurement was possible ($\sim 70\%$ of the total). Superimposed is the expected p_T distribution from charm decay (the shape is similar, regardless of whether the decaying particle is a meson or a baryon) normalised to the number of events with $p_T > 240$ MeV$/c$. It can be seen that reasonably good agreement is obtained for selection A while a clear excess of data is observed at small p_T for region B. This is consistent with a substantial contribution from *white kink* interactions, since their p_T distribution is typically peaked at small values.

For this reason, decays into one particle of region B will not be used for the analysis but only as a consistency check. The data however are useful to determine the contamination of *white kinks* in region A.

[14] The larger interaction lengths quoted in other CHORUS papers have been computed by selecting *white* interactions with transverse momentum larger than 240 MeV$/c$, hence the difference.

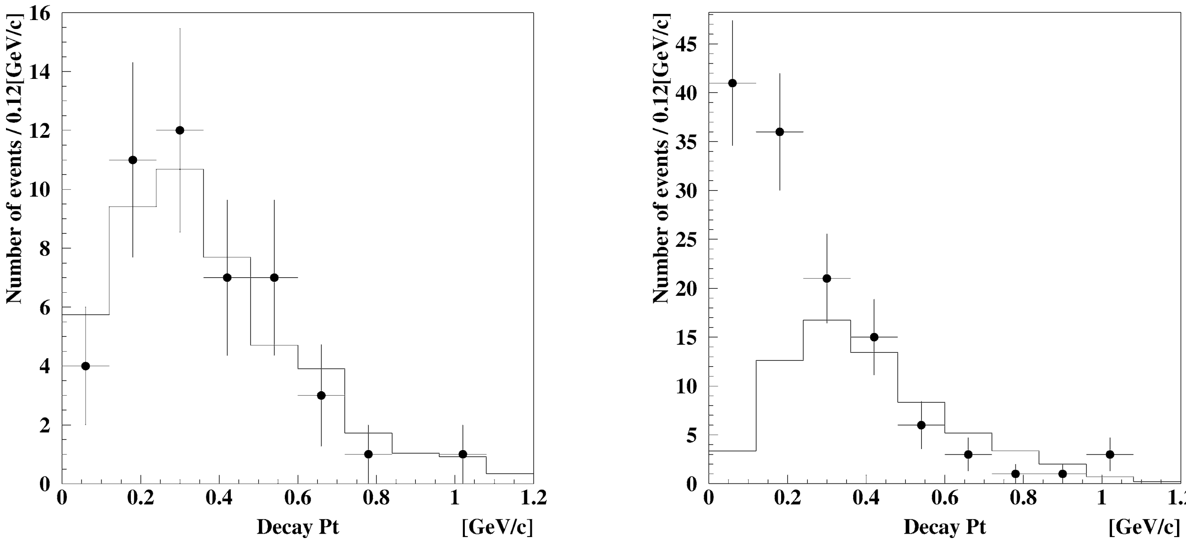

Fig. 4. Decay p_T distribution for a subsample (about 70%) of events from selection A (left) and selection B (right) C1 events. The histograms represent the distribution of charged charm hadrons given by Monte Carlo simulation. Events with $p_T > 240$ MeV/c were used for normalisation.

In fact, in a region of flight lengths where Λ_c^+ are absent and therefore dominated by D^+ and D_s^+ decays, the number of white kink interactions is given by

$$N_{\mathrm{wk}} = N_1 - N_3 \frac{f_1}{f_3}\frac{\varepsilon_1}{\varepsilon_3}, \qquad (1)$$

where N_1 and N_3 are the numbers of C1 and C3 decays, f_1 and f_3 the topological branching ratios of charmed mesons D^+ and D_s^+ averaged over the acceptances and relative abundances, and ε_1, ε_3 are the detection efficiencies for C1 and C3 decays. For the purpose of this calculation, it was assumed that $f_1 = 0.64 \pm 0.07$ and $f_3 = 0.35 \pm 0.07$ for D^+ and $f_1 = 0.62 \pm 0.07$ and $f_3 = 0.35 \pm 0.07$ for D_s^+.

In region B, Monte Carlo simulations indicate that the Λ_c^+ acceptance is about 20% (for deep-inelastic processes). Therefore, Eq. (1) was used in the narrower region 800–2400 µm, indicated with C in what follows, where this acceptance is further reduced to 10%. In this region, $N_1 = 135.4$ and $N_3 = 52.1$ are the (corrected) decay candidates. Assuming a relative abundance $k = D_s^+/D^+ = 0.627 \pm 0.073$ at production [27], the average ratio f_1/f_3 was evaluated to be $1.8^{+0.2}_{-0.6}$, where the errors represent the maximum possible excursion given that both D^+ and D_s^+ have unmeasured decay modes [28].

The detection efficiency ratio $\varepsilon_1/\varepsilon_3$ in the restricted region C under consideration was estimated by the Monte Carlo simulation described in Section 4 and found to be 0.70 ± 0.04.

A background of 6.5 ± 2.1 events expected from $\Sigma^\pm$ decays in region C should also be subtracted from N_1. Eq. (1) would therefore yield an estimation of 63^{+22}_{-7} events due to white kink interactions for region C.

This number is consistent with the calculation using the interaction length for *white kink* as well as with the p_T distribution shown in Fig. 4.

N^A_{wk}, the white kink background in region A (40 µm $< FL <$ 400 µm), was then estimated by means of the relation

$$N^A_{\mathrm{wk}} = N_{\mathrm{wk}} \frac{400\text{–}40}{2400\text{–}800} \frac{\varepsilon^A_{\mathrm{wk}}}{\varepsilon^C_{\mathrm{wk}}} \cdot 0.875 = 9.8^{+4.8}_{-3.7},$$

$\varepsilon^A_{\mathrm{wk}}/\varepsilon^C_{\mathrm{wk}}$, the ratio of *white kink* detection efficiencies in the two regions, was estimated by Monte Carlo simulation and found to be 0.79 ± 0.09. The factor 0.875 is the ratio of number of events analysed with the two selections and takes into account the fact that the two samples are not of identical size. The number of events to be subtracted is also consistent with the p_T distribution shown in Fig. 4 for selection A.

6. Results

The number of decays of type C1 and C3 in the two regions chosen for the analysis may be written as:

$$N_{A1} = Df_1^{D^+} A_A^{D^+} \varepsilon_{A1}^{D^+} + kDf_1^{D_s^+} A_A^{D_s^+} \varepsilon_{A1}^{D_s^+} + \Lambda_c\left(1 - f_3^{\Lambda_c^+}\right) A_A^{\Lambda_c^+} \varepsilon_{A1}^{\Lambda_c^+}, \quad (2)$$

$$N_{A3} = Df_3^{D^+} A_A^{D^+} \varepsilon_{A3}^{D^+} + kDf_3^{D_s^+} A_A^{D_s^+} \varepsilon_{A3}^{D_s^+} + \Lambda_c f_3^{\Lambda_c^+} A_A^{\Lambda_c^+} \varepsilon_{A3}^{\Lambda_c^+}, \quad (3)$$

$$N_{B3} = Df_3^{D^+} A_B^{D^+} \varepsilon_{B3}^{D^+} + kDf_3^{D_s^+} A_B^{D_s^+} \varepsilon_{B3}^{D_s^+} + \Lambda_c f_3^{\Lambda_c^+} A_B^{\Lambda_c^+} \varepsilon_{B3}^{\Lambda_c^+}, \quad (4)$$

where

- N_{A1} and N_{A3} are the numbers of C1 and C3 decays selected by criterion A;
- N_{B3} is the number of C3 decays selected by criterion B;
- D and Λ_c are the numbers of D^+ and Λ_c^+ produced in neutrino interactions;
- The various ε and A represent the efficiencies discussed in Section 4;
- f_i^c ($i = 1, 3$; $c = D^+, D_s^+, \Lambda_c^+$) are the fractions of C1 and C3 decays of each charmed hadron species [28].

As for the calculation of the background, in the above equations, the production of D_s^+ is related to that of D^+ through $D_s^+ = kD$.

The values of the fractions f_i^c and of their estimated errors have already been given for charmed mesons, while $f_3^{\Lambda_c^+}$ is one of the unknowns of the equations and will be determined. The fraction of C1 decays of the Λ_c^+ is assumed to be $(1 - f_3^{\Lambda_c^+})$, therefore, decays into more than three charged particles are neglected at this stage.

N_{B3} are normalised to the number of CC events analysed with selection A.

Because of the similarity of flight-length distributions and efficiencies for D^+ and D_s^+, the values of Λ_c^+ and of the sum of D^+ and D_s^+ do not depend strongly on the assumed value of k. Also to solve the above equations it is necessary to assume the fraction of Λ_c^+ produced through quasi-elastic processes. A value of 0.5 for the ratio $\Lambda_c^+(\mathrm{QE})/\Lambda_c^+(\mathrm{Total})$ at production was used in the analysis and the effects of the uncertainty on this ratio, assumed to be ± 0.5, will be discussed separately.

From Eqs. (3) and (4) the product $\Lambda_c f_3^{\Lambda_c^+}$ was determined to be

$$209 \pm 57(\mathrm{stat}) \pm 13(\mathrm{syst}).$$

This number would become 231 or 201 if Λ_c^+ production occurred totally through quasi-elastic or deep-inelastic processes, respectively.

Other sources of systematic errors—originating from the lack of knowledge of the decay modes of charged charm mesons—have little effect on this measurement.

This result can be used together with Eq. (2) to yield, after proper background subtraction,

$$\Lambda_c = 861 \pm 198(\mathrm{stat}) \pm 98(\mathrm{syst})^{+140}_{-54}(\mathrm{QE})$$

and

$$BR(\Lambda_c^+ \to 3\mathrm{prong}) = 0.24 \pm 0.07(\mathrm{stat}) \pm 0.04(\mathrm{syst}),$$

where the last error on the number of Λ_c^+ represents the effects of the production processes as described above.

As a by-product a value of $1118 \pm 166(\mathrm{stat})$ is obtained for the sum of D^+ and D_s^+. Since charged charm mesons are *background* to the measurements that are addressed in this Letter and since the contributions from D^+ and D_s^+ cannot be separated, an analysis of the systematic errors on the number of D mesons has not been carried out.

Normalising to the number of CC events in the sample, a value of

$$\left(0.37 \pm 0.10(\mathrm{stat}) \pm 0.02(\mathrm{syst})\right) \times 10^{-2}$$

is obtained for the product

$$\frac{\sigma(\Lambda_c^+)}{\sigma(\mathrm{CC})} BR(\Lambda_c^+ \to 3\mathrm{prong}).$$

Similarly

$$\left(1.54 \pm 0.35(\mathrm{stat}) \pm 0.18(\mathrm{syst})\right) \times 10^{-2}$$

is measured for $\sigma(\Lambda_c^+)/\sigma(\mathrm{CC})$.

Quasi-elastic production would cause the above values to be in the range (0.36–0.41) $\times 10^{-2}$ and (1.45–1.80) $\times 10^{-2}$, respectively, depending on whether the production is completely quasi-elastic or deep-inelastic.

This analysis also measures that $(43 \pm 8 \pm 6)\%$ of all charged charm hadrons produced in neutrino interactions are Λ_c^+. This value is in agreement with the earlier measurement of $(29^{+15}_{-9})\%$ reported by E531 [14].

7. Conclusions

In summary, the production of Λ_c^+ in about 50 000 νN charged-current interactions has been studied. From a sample of charged charm decays, larger than previously collected by similar experiments, the Λ_c^+ signal was extracted statistically on the basis of the flight-length. The product of cross-section relative to ν_μ CC times $BR(\Lambda_c^+ \to 3\text{prong})$ was measured as well as the relative cross-section itself and the branching ratio. Most of the systematic uncertainty on these measurements comes from the lack of knowledge of the charged charm meson topological decay modes and from the unknown fraction of Λ_c^+ produced through quasi-elastic processes. An analysis to measure this fraction is in progress. The sample analysed for this Letter is only a quarter of what is available at the moment in CHORUS, therefore, improvements on the statistical errors are expected.

Acknowledgements

We gratefully acknowledge the help and support of the neutrino-beam staff and of the numerous technical collaborators who contributed to the detector construction, operation, emulsion pouring, development, and scanning. The experiment has been made possible by grants from the Institut Interuniversitaire des Sciences Nucléaires and the Interuniversitair Instituut voor Kernwetenschappen (Belgium); the Israel Science Foundation (Grant 328/94) and the Technion Vice President Fund for the Promotion of Research (Israel); CERN (Geneva, Switzerland); the German Bundesministerium für Bildung und Forschung (Germany); the Institute of Theoretical and Experimental Physics (Moscow, Russia); the Istituto Nazionale di Fisica Nucleare (Italy); the Promotion and Mutual Aid Corporation for Private Schools of Japan and Japan Society for the Promotion of Science (Japan); the Korea Research Foundation (Grant KRF-2001-005-D00006) (Republic of Korea); the Foundation for Fundamental Research on Matter FOM and the National Scientific Research Organization NWO (The Netherlands); and the Scientific and Technical Research Council of Turkey (Turkey).

We gratefully acknowledge their support.

References

[1] H. Abramowicz, et al., CDHS Collaboration, Z. Phys. C 15 (1982) 19.
[2] S.A. Rabinowitz, et al., CCFR Collaboration, Phys. Rev. Lett. 70 (1993) 134.
[3] M. Jonker, et al., CHARM Collaboration, Phys. Lett. B 107 (1981) 241.
[4] P. Vilain, et al., CHARM II Collaboration, Eur. Phys. J. C 11 (1999) 19.
[5] P. Astier, et al., NOMAD Collaboration, Phys. Lett. B 486 (2000) 35.
[6] M. Goncharov, et al., NuTeV Collaboration, Phys. Rev. D 64 (2001) 112006.
[7] J. Blietschau, et al., Phys. Lett. 86B (1979) 108.
[8] P. Astier, et al., NOMAD Collaboration, Phys. Lett. B 526 (2002) 278.
[9] M. Calicchio, et al., BEBC-TST Collaboration, Phys. Lett. B 93 (1980) 521.
[10] H. Grassler, et al., Phys. Lett. 99B (1981) 159.
[11] P.C. Bosetti, et al., Phys. Lett. 109B (1981) 234.
[12] D. Son, et al., Phys. Rev. Lett. 49 (1982) 1128.
[13] Yu.A. Batusov, et al., JETP Lett. 46 (1987) 268;
V.V. Ammosov, et al., JETP Lett. 58 (1993) 247.
[14] N. Ushida, et al., E531 Collaboration, Phys. Lett. B 206 (1988) 375.
[15] E. Eskut, et al., CHORUS Collaboration, Phys. Lett. A 401 (1997) 7.
[16] T. Nakano, Ph.D. Thesis, Nagoya University, Japan, 1997.
[17] T. Nakano, Proceedings of International Europhysics Conference on HEP 2001.
[18] K. Kodama, et al., Nucl. Instrum. Methods A 493 (2002) 45.
[19] GEANT 3.21, CERN program library long write up W5013.
[20] P. Zucchelli, Ph.D. Thesis, Università di Ferrara, Italy, 1995.
[21] G. Ingelman, Preprint TSL/ISV 92-0065, Uppsala University, Sweden, 1992.
[22] T. Sjöstrand, Comput. Phys. Commun. 82 (1994) 74.
[23] S. Ricciardi, Ph.D. Thesis, Università di Ferrara, Italy, 1996.
[24] R.E. Shrock, B.W. Lee, Phys. Rev. D 16 (1976) 2539.
[25] A. Fassò, et al., SARE-3 Workshop, KEK Report Proceedings 97-5, 1997, p. 32.
[26] A. Satta, Ph.D. Thesis, Università degli Studi di Roma, Italy, 2001.
[27] G. De Lellis, et al., Phys. Lett. B 550 (2002) 16.
[28] C.G. Wohl, Particle Data Group note, 2002 (unpublished).