Measurement of $\Lambda_c^+$ production in neutrino charged-current interactions

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Abstract

A measurement of $\Lambda_c^+ / \Lambda_c^+ c$ 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 $\Lambda_c^+$ to be defined. At an average neutrino energy of 27 GeV, the product $\sigma(\Lambda_c^+/\Lambda_c^- c) / \sigma(CC) \times BR(\Lambda_c^+ \rightarrow 3p)$ was measured to be $(0.37 \pm 0.02(stat) \pm 0.07(syst)) \times 10^{-2}$, while the values of $(1.54 \pm 0.35(stat) \pm 0.18(syst)) \times 10^{-2}$ and of $0.24 \pm 0.07(stat) \pm 0.04(syst)$ were obtained for $\sigma(\Lambda_c^+) / \sigma(CC)$ and $BR(\Lambda_c^+ \rightarrow 3p)$, respectively.

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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 with a contamination of 6% $\bar{\nu}_\mu$ and $\sim$1% of $\nu_e$. The original search was optimised to detect muonic decays of the $\tau$ 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 $\nu_\mu$ CC interactions the muon track, reconstructed by the scintillating fibre system, was searched for in the interface emulsion sheet with a 90 $\mu$m 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 $\mu$m 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 $5.06 \times 10^{19}$ protons on target. The beam consists mainly of $\nu_\mu$ with a contamination of 6% $\bar{\nu}_\mu$ and $\sim$1% of $\nu_e$. The original search was optimised to detect muonic decays of the $\tau$ 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 $\nu_\mu$ 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 $\nu_\mu$ CC events have been located in emulsion so far as a result of this procedure. Within a volume of 1.5 mm $\times$ 1.5 mm $\times$ 6.3 mm around the position where the $\mu^-$ 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

2. Experimental apparatus

CHORUS was designed to search for $\nu_\mu \rightarrow \nu_\tau$ oscillation through the detection of the characteristic topology of the $\tau$-lepton decay in $\nu_\tau$ 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 $\mu$m layers of emulsion on either side of a 90 $\mu$m plastic base of size 36 $\times$ 72 cm$^2$; 36 plates form a module. Each stack is followed by three interface emulsion sheets with a 90 $\mu$m emulsion layer on both sides of a 800 $\mu$m 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 $\mu$m in position and 2 mrad in angle.
presented in this Letter are based on a sample of about 50 000 $\nu_\mu$ 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 $\Lambda_c^+$ 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 $\mu$m and less than 30 $\mu$m. 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 $\mu$m.
- 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 $\mu$m.

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 $\mu$ 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.

<table>
<thead>
<tr>
<th>Decay type</th>
<th>Selection A</th>
<th>Selection B</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>70</td>
<td>165</td>
</tr>
<tr>
<td>C3</td>
<td>84</td>
<td>103</td>
</tr>
<tr>
<td>C5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>N2</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>N4</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>273</td>
</tr>
</tbody>
</table>

Table 2
Classification of candidates rejected as possible decays.

<table>
<thead>
<tr>
<th>Type</th>
<th>Selection A</th>
<th>Selection B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low momentum</td>
<td>566</td>
<td>41</td>
</tr>
<tr>
<td>Traversing tracks</td>
<td>542</td>
<td>122</td>
</tr>
<tr>
<td>Nuclear fragment</td>
<td>105</td>
<td>37</td>
</tr>
<tr>
<td>γ-conversion</td>
<td>46</td>
<td>6</td>
</tr>
<tr>
<td>Hadron interactions</td>
<td>29</td>
<td>97</td>
</tr>
<tr>
<td>Reconstruction failure</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>1307</td>
<td>313</td>
</tr>
</tbody>
</table>

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 56761 $\nu_\mu$ CC events with $p_\mu > 30$ GeV/c 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 accounted for by applying a correction. The location of events with $p_\mu > 30$ 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 $v_\mu$ CC events with $p_\mu > 30$ GeV/c to $p_\mu < 30$ GeV/c has been measured to be $0.381 \pm 0.001$, a weight has been applied to the analysed events with $p_\mu > 30$ GeV/c in such manner that the ratio to those with $p_\mu < 30$ 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.

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 $\Lambda^+_{c} \rightarrow \Sigma^+_{c}$ 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 $\Lambda^+_c \rightarrow \Sigma^+_{c}$, since no decay products of charm other than $\Sigma^-$ 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 $\Lambda^+_c \rightarrow \Sigma^\pm$. In the context
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 $\Lambda_c^+$ 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 $\Lambda_c^+$ 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 $\nu_\mu$ CC events was estimated using the muon momentum spectrum given by Monte Carlo simulation. They were found to be $0.99 \pm 0.01$ for $\Lambda_c^+$, produced in deep-inelastic processes, $1.24 \pm 0.01$ for $\Lambda_c^+$ produced in quasi-elastic processes (including $\Sigma_c^+$ and $\Sigma_c^{++}$), $0.90 \pm 0.01$ for $D^+$, and $0.89 \pm 0.01$ 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 ($\varepsilon_{A1}$, $\varepsilon_{A3}$, $\varepsilon_{B1}$, $\varepsilon_{B3}$) 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 charged hadrons. For $\Lambda_c^+$ 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-
from K of type C1, while it is negligible for the sample defined by selection B and decays into a final state and having no nuclear activity, an interaction length of \( \sim 2 \text{ m} \), averaged over the momentum 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 \( p_T > 240 \text{ MeV}/c \). 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.

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 \( \sim 66 \text{ m} \), averaged over the momentum spectrum of pions produced in \( \nu N \) 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 \( \sim 2.5 \text{ m} \) 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 \( p_T > 240 \text{ MeV}/c \). 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.

\begin{table}
\begin{tabular}{cccc}
\hline
 & \( A_n \) & \( \Lambda_n \) & \( \Lambda_n \) & \( D_n \) & \( D_n \) \\
\hline
\( A_1 \) & 0.573 \( \pm 0.010 \) & 0.584 \( \pm 0.005 \) & 0.171 \( \pm 0.005 \) & 0.280 \( \pm 0.008 \) \\
\( A_{A1} \) & 0.145 \( \pm 0.015 \) & 0.104 \( \pm 0.007 \) & 0.187 \( \pm 0.017 \) & 0.166 \( \pm 0.020 \) \\
\( A_{A3} \) & 0.437 \( \pm 0.018 \) & 0.341 \( \pm 0.010 \) & 0.363 \( \pm 0.018 \) & 0.429 \( \pm 0.022 \) \\
\( A_B \) & 0.193 \( \pm 0.008 \) & 0.019 \( \pm 0.001 \) & 0.446 \( \pm 0.006 \) & 0.508 \( \pm 0.009 \) \\
\( B_n \) & 0.226 \( \pm 0.028 \) & 0.070 \( \pm 0.052 \) & 0.253 \( \pm 0.012 \) & 0.252 \( \pm 0.018 \) \\
\hline
\end{tabular}
\caption{Geometrical acceptance and efficiency for decays of charmed hadrons}
\end{table}
In fact, in a region of flight lengths where $\Lambda_c^+$ are absent and therefore dominated by $D^+$ and $D_s^+$ decays, the number of white kink interactions is given by
\[ N_{wk} = N_1 - N_3 \frac{f_1 \epsilon_1}{f_3 \epsilon_3}, \tag{1} \]
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 $\epsilon_1$, $\epsilon_3$ 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 $\Lambda_c^+$ 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 $1.8_{-0.6}^{+0.2}$, where the errors represent the maximum possible excursion given that both $D^+$ and $D_s^+$ have unmeasured decay modes [28].

The detection efficiency ratio $\epsilon_1/\epsilon_3$ in the restricted region C under consideration was estimated by the Monte Carlo simulation described in Section 4 and found to be $0.70 \pm 0.04$.

A background of $6.5 \pm 2.1$ events expected from $\Sigma^\pm$ decays in region C should also be subtracted from $N_1$; Eq. (1) would therefore yield an estimation of $63_{-7}^{+22}$ 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. $N_{wk}^A$, the white kink background in region A (40 µm $< FL < 400$ µm), was then estimated by means of the relation
\[ N_{wk}^A = N_{wk} \frac{400-40}{2400-800} \frac{\epsilon_{wk}^A}{\epsilon_{wk}^C} \cdot 0.875 = 9.8_{-3.7}^{+4.8}. \]

$\epsilon_{wk}^A/\epsilon_{wk}^C$, the ratio of white kink detection efficiencies in the two regions, was estimated by Monte Carlo simulation and found to be $0.79 \pm 0.09$. 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:

$$N_{A1} = Df^+_1 A^+_A \varepsilon_{A1}^+ + kDf^+_2 A^+_A \varepsilon_{A1}^+$$

$$+ A_c (1 - f^+_3) A^+_A \varepsilon_{A1}^+ , \quad (2)$$

$$N_{A3} = Df^+_3 A^+_A \varepsilon_{A3}^+ + kDf^+_4 A^+_A \varepsilon_{A3}^+$$

$$+ A_c f^+_3 A^+_A \varepsilon_{A3}^+ , \quad (3)$$

$$N_{B3} = Df^+_5 A^+_B \varepsilon_{B3}^+ + kDf^+_6 A^+_B \varepsilon_{B3}^+$$

$$+ A_c f^+_3 A^+_B \varepsilon_{B3}^+ , \quad (4)$$

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 $A_c$ are the numbers of $D^+$ and $\Lambda^+_c$ produced in neutrino interactions;
- The various $\varepsilon$ and $A$ represent the efficiencies discussed in Section 4;
- $f^+_i (i = 1, 3; c = D^+, D^+_c, \Lambda^+_c)$ 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 $D^+_c$ is related to that of $D^+$ through $D^+_c = kD^+$.

The values of the fractions $f^+_i$ and of their estimated errors have already been given for charmed mesons, while $f^+_3$ is one of the unknowns of the equations and will be determined. The fraction of C1 decays of the $\Lambda^+_c$ is assumed to be $(1 - f^+_3)$; 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 $D^+_c$, the values of $\Lambda^+_c$ and of the sum of $D^+$ and $D^+_c$ do not depend strongly on the assumed value of $k$. Also to solve the above equations it is necessary to assume the fraction of $\Lambda^+_c$ produced through quasi-elastic processes.

A value of 0.5 for the ratio $\Lambda^+_c$(QE)/$\Lambda^+_c$(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 $A_c f^+_3 A^+_c$ was determined to be

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

This number would become 231 or 201 if $\Lambda^+_c$ 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,

$$\Lambda_c = 861 \pm 198 \text{(stat)} \pm 98 \text{(syst)}^{+140}_{-36} \text{(QE)}$$

and

$$BR(\Lambda^+_c \rightarrow 3\text{prong}) = 0.24 \pm 0.07 \text{(stat)} \pm 0.04 \text{(syst)},$$

where the last error on the number of $\Lambda^+_c$ represents the effects of the production processes as described above.

As a by-product a value of $1118 \pm 166 \text{(stat)}$ is obtained for the sum of $D^+$ and $D^+_c$. Since charged charm mesons are background to the measurements that are addressed in this Letter and since the contributions from $D^+$ and $D^+_c$ 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

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

is obtained for the product

$$\frac{\sigma(\Lambda^+_c)}{\sigma(\text{CC})} BR(\Lambda^+_c \rightarrow 3\text{prong}).$$

Similarly

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

is measured for $\sigma(\Lambda^+_c)/\sigma(\text{CC})$.

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 \(\Lambda_c^+\). This value is in agreement with the earlier measurement of \((29^{+15}_{-9})\%\) reported by E531 [14].

7. Conclusions

In summary, the production of \(\Lambda_c^+\) in about 50,000 \(\nu N\) charged-current interactions has been studied. From a sample of charged charm decays, larger than previously collected by similar experiments, the \(\Lambda_c^+\) signal was extracted statistically on the basis of the flight-length. The product of cross-section relative to \(\nu\mu\) CC times \(BR(\Lambda_c^+ \rightarrow 3\text{prong})\) 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 \(\Lambda_c^+\) 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.

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