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Observation of one event with the characteristics of associated charm production in neutrino charged-current interactions

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Abstract

We report on a search for associated charm production in neutrino charged-current interactions in the CHORUS experiment, based on the visual observation of charmed-particle decays. The search differs from those carried out so far in which the production of $c\bar{c}$ has been inferred from measurements of events with two or three muons in the final state, resulting from the decay of charmed hadrons. One event with a double charm-decay topology has been found and a corresponding background of 0.04 events has been evaluated.

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1. Introduction

In this Letter we present the results of a search for associated charm production in neutrino nucleon charged-current (CC) interactions. Therefore, the process is of the type

$$\nu_\mu N \to \mu^- c\bar{c}X \qquad (1)$$

in which the charm–anticharm pair is produced by a gluon emitted via bremsstrahlung from a light parton.

In the past, results on the cross-section for process (1) have been obtained by estimating the production rates of prompt trimuons [1] and like-sign dimuons ([2,3]). The underlying assumption was that the $\mu^+ \mu^-$ pair or the μ^-, observed in addition to the leading μ^-, was produced by the muonic decay of charmed hadrons. All measurements have yielded rates higher than expected on the basis of QCD calculations [4] but all were obtained after the subtraction of a large background of *non-prompt* muons (e.g., from decays of non-charmed hadrons) from initial samples of multi-muon events.

The search subject of this Letter is substantially different from those carried out so far since it relies on the visual observation of the two vertices corresponding to the decay of the charmed particles: an observation that would be possible because of the spatial resolution of nuclear emulsions that are the neutrino target in the CHORUS experiment.

2. The experimental setup

The CHORUS experiment was designed to search for $\nu_\mu \to \nu_\tau$ oscillation in the SPS Wide-Band Neutrino Beam at CERN through the direct observation of the tau decay in nuclear emulsions. Since charmed particles have a flight length comparable to that of the tau lepton, the experiment is also suitable to study charm production. The West Area Neutrino Facility (WANF) of the CERN SPS provides an intense beam of ν_μ with an average energy of 27 GeV.

The experiment follows a *hybrid* design. The setup, described in detail in Ref. [5], is composed of an emulsion target, a scintillating fibre tracker system, trigger hodoscopes, a hadron spectrometer, a lead-scintillator calorimeter and a muon spectrometer.

The event search in emulsion relies on predictions on the basis of tracks reconstructed in the electronic detectors which also serve to measure the event kinematics. Nuclear emulsions, packed into stacks of 36 sheets, each 790 µm thick, are used as an active target. Their sub-micron resolution makes it possible to detect short-lived particles directly. The momentum of charged particles can also be determined from the measurement of the deviations due to multiple Coulomb scattering.

During the four years of exposure more than 10^6 neutrino interactions were accumulated in the 770 kg emulsion target and about $\mathcal{O}(10^4)$ led to the production of a charmed particle.

3. The search

This search was applied to interactions with at least one identified muon located in emulsion and obtained during the 1996 and 1997 exposures, for a total of 31 226 and 36 842 events, respectively.

The idea at the basis of the search for associated charm production was to start with the sample of already located single charm events and to search for the charmed partner in these events. Since about three-quarters of the double charm events were expected to contain at least one D^0—a signature with very low topological background—the initial sample was based on a selection of events with a D^0 decay topology. To further improve background rejection, the decay vertex was required to be in the same emulsion sheet as the primary vertex. This results in an average flight length of less than 400 µm.

Neutrino interaction vertices were found in the emulsion plates by following in the upstream direction negatively charged tracks reconstructed with the target tracker system (TT). This *scan-back* procedure used emulsion track segments reconstructed in the most upstream 100 µm of each plate. The plate where no segment is found on the track is defined as the *vertex plate*. It contains the primary neutrino vertex or the secondary (decay) vertex, or both. This *vertex location* procedure was performed during the ν_τ search.

After the vertex location, the event search can thus be divided into two consecutive steps: first a search for the D^0 decay in the vertex plate and then a search for the decay of the charmed partner.

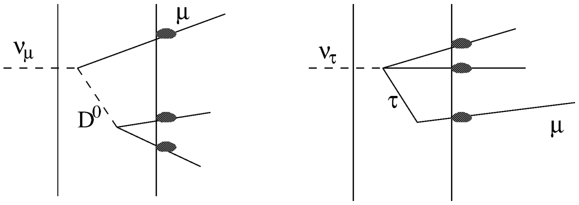

Fig. 1. Topology of ν_μ interactions with D^0 production and subsequent in-plate D^0 decay (left) compared to ν_τ interactions with subsequent in-plate tau decay (right). The shaded regions on the tracks indicate the 100 µm layer where tracks are automatically searched for in emulsion.

3.1. Location of the neutral D meson

The topology of ν_μ CC interactions with charmed hadron production and subsequent decay is similar to that of ν_τ CC interactions with muonic tau decay (see Fig. 1). Hence, the method used to search for tau decays is expected to find charmed particles as well. The tau decay search procedure is described in Ref. [8].

Events with at least one track that has a large impact parameter with respect to the reconstructed vertex were selected as candidates either for the decay of a tau lepton into a muon or for charm production in ν_μ interactions (see Fig. 1). From the sample of 68 068 events several hundred were thus selected for a manual check. A total of 98 events containing a D^0 decay topology were confirmed as neutral particle decays by this manual scan, which also included a precise re-measurement of all track parameters [9].

The detection efficiency was estimated to be $(2.13 \pm 0.42)\%$ by a full simulation[16] of the selection procedure. This efficiency is essentially made of three contributions: the event reconstruction and location ($\sim 48\%$), the requirement of a decay in the vertex plate ($\sim 35\%$) and the decay finding efficiency ($\sim 12\%$). The efficiency for the detection of either the D^0 or the $\overline{D}^0$ was estimated to be $(4.2 \pm 0.8)\%$.

Two-body decays of the Λ and K_s^0 can also contribute to the two-prong decay topologies. The two-prong D^0 decays have predominantly more than two particles in the final state. Therefore, in two-prong topologies, a further selection based on the acoplanarity of the decay was used. The acoplanarity angle ϕ was defined as the angle between the parent particle and the plane formed by the daughter particles. A cut on this angle was applied ($|\phi| > 10$ mrad) to reduce the background of Λ and K_s^0 decays. The efficiency of this criterion was included in the $\varepsilon_{\mathrm{kin}}$ factor in Table 1.

Table 1
Detection efficiencies in the search for the associated production of a D^0 with either a charged or a neutral charmed partner. $\varepsilon_{\mathrm{tot}}$ is the overall detection efficiency in each channel, ε_{D^0} the efficiency to find the first D^0 and $\varepsilon_{\mathrm{kin}}$ the efficiency of the kinematical selection criteria. The quoted error is only statistical. $\varepsilon_{\mathrm{sum}}$ is the sum of the overall efficiencies and includes also the systematic error

Sample	neutral + charged	neutral + neutral
Hadr. fraction	0.496 ± 0.006	0.243 ± 0.004
ε_{D^0}	0.0213 ± 0.0013	0.042 ± 0.003
$\varepsilon_{\mathrm{kin}}$	0.49 ± 0.04	0.61 ± 0.03
$\varepsilon_{\mathrm{tot}}$	$(5.2 \pm 0.5) \times 10^{-3}$	$(6.2 \pm 0.5) \times 10^{-3}$
$\varepsilon_{\mathrm{sum}}$	$(11.4 \pm 0.7 \pm 2.3) \times 10^{-3}$	

3.2. Search for the D^0 partner

The search for the charmed partner of the D^0 was carried out by looking for both neutral and charged charmed hadrons. It was necessary to validate the outgoing particles in neutral-particle decays with the electronic detector to assign the parent particle to the appropriate neutrino interaction. Moreover, the fibre-tracker information was used to efficiently tag potential decay candidates among the primary-vertex tracks by requiring that a corresponding TT track was not found. In the search for the neutral partner of the D^0, events for which all TT tracks were already matched with those measured in emulsion (i.e., those at the primary vertex and at the D^0 decay-vertex) were excluded.

3.3. Neutral charmed-partner search

Events with at least one TT track not matching any track measured at the primary vertex within 20 mrad were selected. The search for neutral charmed partners was performed by means of the *netscan* technique [10]: a wide angle scanning (±400 mrad) of a given area in a sequence of emulsion plates.

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[16] The process (1) was simulated using the Herwig event generator [6]. Its output was passed through the CHORUS detector simulator based on the GEANT package [7]. The generated events were analyzed with the CHORUS event reconstruction program.

The scanning volume was defined as a square with 2 mm sides along ten plates downstream of the vertex. All tracks originating in this volume were combined to build vertices using their distance of closest approach. If a secondary vertex consisting of at least one track matching a TT track was found, a visual check was carried out to confirm it. No event with a second D^0 decay was found.

Emulsion tracks were required to have segments in at least three plates so that the effective fiducial volume is defined by the scanned area of 2×2 mm^2 perpendicular to the beam direction and seven plates along the beam. To reject background, an acoplanarity cut similar to the one described previously was applied and furthermore the transverse momentum of both decay products (relative to the direction of flight of the neutral particle) was required to be larger than 250 MeV/c. These contributions to the detection efficiency are included in $\varepsilon_{\mathrm{kin}}$ (Table 1). The overall detection efficiency was determined to be $(6.2 \pm 0.5) \times 10^{-3}$.

3.4. Charged charmed-partner search

The search for a charged charmed hadron was carried out by visually following in the downstream direction all tracks attached to the primary vertex which did not match any reconstructed track in the TT within an angular tolerance of 20 mrad in both projections. It was required that these tracks were emitted at an angle of less than 400 mrad with respect to the perpendicular to the emulsion plates. The visual *follow-down* was performed along five plates (~ 4 mm) downstream of the vertex plate. In the sample of 98 events with a D^0 decay topology, 78 tracks satisfied the above criteria. A total track length of about 31 cm was manually scanned in the emulsion during this follow-down procedure.

Kink candidates were accepted if the daughter had a transverse momentum with respect to the parent trajectory of $p_\perp > 250$ MeV/c and a momentum of $p > 600$ MeV/c. The contributions of these cuts to the detection efficiency were included in $\varepsilon_{\mathrm{kin}}$ (Table 1). The overall detection efficiency was estimated to be $(5.2 \pm 0.5) \times 10^{-3}$.

One event with a double charm-decay topology was found, described in detail in Section 4.

4. The candidate event

The topology of the candidate event as seen in the emulsion is schematically shown in Fig. 2. Table 2 shows the list of all particles measured at the primary and secondary vertices, together with their emission angles. To estimate the lifetime of the decaying particles we have used the relation $c\tau = L\langle\theta\rangle$ [11], where $\langle\theta\rangle$ is the average emission angle of the daughter particles relative to the parent direction and L is the flight length. The estimated lifetime is well consistent with that of charmed particles. At the primary vertex there are six 'black' tracks from the nuclear break-up and two minimum-ionizing tracks: one is the negative

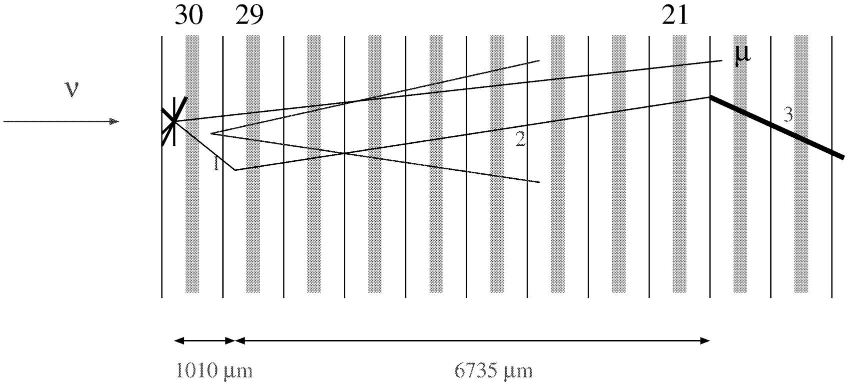

Fig. 2. Sketch of the event topology in emulsion. Emulsion plates are indicated by two vertical white bars (the sensitive emulsion layers) around a shaded vertical bar (the plastic base). A discussion of the tracks can be found in the text.

Table 2
List of particles measured at primary and secondary vertices

Particle ID	θ_Y (rad)	θ_Z (rad)	$\tau = L\langle\theta\rangle/c$
μ^-	0.009	0.104	
C^0	−0.047	−0.055	2.8×10^{-13} s
Particle 1	−0.102	0.020	1.4×10^{-12} s
C^0 daughter	0.267	0.188	
C^0 daughter	−0.139	−0.054	
Particle 2	−0.495	−0.120	

muon and the other is the kink parent, denoted as particle 1 in Table 2.

A neutral particle (C^0) decays in the same emulsion plate, 340 µm downstream of the primary vertex. Two particles emerge from the neutral-particle decay point, both matching a TT track. The acoplanarity of parent and daughter particles, $\phi = (0.048 \pm 0.005)$ rad, rules out a two-body decay and thus both the K_s^0 and the Λ hypotheses. Given also the short (340 µm) flight length, the natural assignment is a neutral charmed-meson decay: either D^0 or $\overline{D}^0$.

The muon and both D^0 daughters are reconstructed in the electronic trackers. The fourth track seen in the vertex plate (particle 1) has been followed down in the search for a secondary vertex. After a path of 1010 µm it shows a kink 30 µm upstream of the plastic base. The kink angle is 417 mrad. The secondary vertex is compatible with a decay (no visible nuclear recoil or Auger electrons). The outgoing particle (particle 2), after travelling 7560 µm, shows either a kink or a secondary interaction with only one outgoing particle (particle 3) emitted with angles $(-0.191, -0.164)$ rad, 307 mrad from the parent direction. The emulsion conditions do not allow the distinction between a secondary interaction and a decay in this case. The measurement of the grain density along the track of particle 2 is compatible with minimum ionization. The ionization of particle 3 is about twice that of a minimum-ionizing particle.

The $p\beta$ measurement by multiple scattering for particle 2 could not be performed because of its large emission angle and short length. In contrast, particle 3 travels across 20 emulsion plates and its multiple scattering could be measured. By combining this measurement of $p\beta$ with the measurement of the ionization in the emulsion, we could assert that particle 3 is a proton of momentum $p_3 = 780^{+170}_{-110}$ MeV$/c$. Using the relation $p_2 \geqslant p_3$, a minimum transverse momentum at the first kink of $p_{\perp\min} = 330^{+70}_{-50}$ MeV$/c$ was estimated.

5. Background evaluation

The background to associated charm production comes predominantly from events in which a single charmed particle is produced and the decay or interaction of one of the non-charmed hadrons in the final state mimics the decay of a charmed partner. All possible background sources of this type have been evaluated through simulation. The relevant contributions, after applying the geometrical and kinematical selection criteria of Section 3.2, are listed in Table 3 for the *neutral/charged* channel and Table 4 for the *neutral/neutral* channel.

We discuss here the kinematical selection criteria mentioned in Section 3.2, applied to reduce background.

Most hadronic interactions can be distinguished from decays by their visible nuclear recoil or Auger electrons. The remaining interactions, ‘white kinks’, are characterized by a long interaction length and a steeply falling transverse momentum distribution.

Table 3
The background processes and corresponding event yields in the *neutral/charged* channel

Process	Note	Event yield ($\times 10^{-3}$)
$\nu_\mu N \to \mu^- c^+ X$	K_s^0 (from primary) in-plate decay	0.6
$\nu_\mu N \to \mu^- c^+ X$	K_s^0 (from c^+ decay) in-plate decay	1.6
$\nu_\mu N \to \mu^- c^+ X$	Λ (from primary) in-plate decay	1.3
$\nu_\mu N \to \mu^- c^+ X$	Λ (from c^+ decay) in-plate decay	0.2
$\nu_\mu N \to \mu^- D^0 X$	white charged interaction	34
Overall		38 ± 8

Table 4
The background processes and corresponding event yields in the *neutral/neutral* channel

Process	Note	Event yield ($\times 10^{-3}$)
$\nu_\mu N \to \mu^- D^0 X$	K_s^0 (from primary) decay	0.5
$\nu_\mu N \to \mu^- D^0 X$	K_s^0 (from D^0) decay	0.25
$\nu_\mu N \to \mu^- D^0 X$	Λ (from primary) decay	0.07
$\nu_\mu N \to \mu^- D^0 X$	white interaction	4
Overall		4 ± 1

White kinks can therefore be rejected by requiring a large decay $p_\perp$. A cut on the daughter momentum is also relevant to have control over the background sources.

Restricted to $p_\perp > 250$ MeV$/c$ and $p > 600$ MeV$/c$, the mean interaction length for the white-kink process evaluated using FLUKA [12] is (17 ± 3) m, in agreement with the background analysis performed in the oscillation search [8].[17] Including also the contribution from 'white' tridents, a background of $(34 \pm 7) \times 10^{-3}$ events can be expected in the sample of 98 events for which a charged charm partner has been searched for.

The decay $p_\perp$ is also the most effective kinematical variable to reject π and K decays, the contribution of which to the background is already small owing to their long flight length. The $p_\perp > 250$ MeV$/c$ cut practically eliminates this background source. As far as neutral decays are concerned, we can observe the following.

- The acoplanarity cuts strongly reduce the background from decays of K^0 and Λ particles emitted at the primary vertex. The cut is less effective if the strange particle is produced at the charm-decay vertex. For this reason, in the *neutral/neutral* channel, the acoplanarity cut on the downstream decay was applied by considering either the primary vertex or the upstream neutral decay as possible origins.
- The background from K^0 and Λ interactions, evaluated using FLUKA [12], is reduced by the requirement that no nuclear activity should be seen at the interaction point.

The main background source is therefore given by the white-kink interactions. An overall background of $(42 \pm 8) \times 10^{-3}$ events is thus expected.

6. Conclusions

We have carried out a search for associated charm production using the double-decay signature in muon-neutrino CC interactions. One event with a clear double charm-decay topology has been found. It consists of a primary vertex with a negative muon attached, a neutral particle decaying in the same emulsion plate and a charged particle decaying about 1 mm downstream of the neutrino vertex. The estimated lifetime is consistent with that of charmed hadrons. The observed event therefore has the characteristics of associated charm production and, given the low background, it can be considered as evidence for this process.

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[17] A recent experimental determination [13] has shown a longer interaction length which would lead to a factor three reduction of this background source.

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