PROCEEDINGS OF SCIENCE

Charm production cross-sections

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During the years 1994–97, the emulsion target of the CHORUS detector was exposed to the wide-band neutrino beam of the CERN SPS of 27 GeV average neutrino energy. In total about 100, 000 charged-current neutrino interactions with at least one identified muon were located in the nuclear emulsion target and fully reconstructed, using newly developed automatic scanning systems. Charmed particles were searched for by a program recognizing particle decays. This technique, based on the observation of the decay in nuclear emulsion, allows the selection of a sample with very low background and minimal kinematical bias. 2013 charged-current interactions with a charmed hadron in the final state were selected and confirmed through visual inspection. Some of the CHORUS measurements and their implications for future neutrino experiments are discussed in this paper.

10th International Workshop on Neutrino Factories, Super beams and Beta beams
June 30 - July 5 2008
Valencia, Spain

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PoS(NuFact08)047

1. Physics motivation

The study of the charmed particles is still a challenging field of particle physics. In particular, the neutrino induced charm-production offer the possibility to study the strange-quark content of the nucleon, to measure "directly" the CKM matrix element V_{cd} and to test models for charm-production and subsequent hadronization.
In addition to its intrinsic interest, an improved knowledge of charm production helps to better understand the charm background in neutrino oscillation experiments where the signal serched for is given by the production of a τ lepton or of muons of apparenly 'wrong' charge with the respect to that expected from the neutrino beam helicity, as in ongoing experiments [1] and at future neutrino facilities [2].

CHORUS experiment is based on the use of a hybrid nuclear emulsion detector. In nuclear emulsion, charmed particles are recognized on the basis of their short flight length and characteristic decay topology, so that the required kinematic cuts can be quite loose. All decay channels are therefore observed, not only the muonic ones, with no required knowledge of muonic branching ratios and with very low background. For automated decay search in emulsion a new very fast scanning system called 'Ultra Track Selector' (UTS) [3] has been used. A high-statistics sample of charm decays in emulsion has thus been collected as reported in this paper.

2. The CHORUS experiment

The CHORUS experiment [4] was designed to search for $\nu_\mu \to \nu_\tau$ oscillations in the SPS Wide Band Neutrino Beam at CERN through the direct observation of the τ lepton decay. The detector is a hybrid setup that combines a nuclear emulsion target of 770 Kg with various electronic detectors. The target region is followed by a hadron spectrometer, an electromagnetic and hadronic calorimeter, and a muon spectrometer, respectively.
From the sample of 93807 defined charged-current events, 2752 events have been selected by a program which preserves a high efficiency for decay vertices and rejects most background topologies. These events have been visually inspected to confirm the decay topology. A secondary vertex is accepted as a decay if the number of charged particles is consistent with charge conservation and no other activity (Auger-electron or visible recoil) is observed. This procedure select 2013 charm candidates.

3. Charm cross-sections

Chorus results based on the analysis of the visually checked charm sample are reported in the following.

3.1 D^0 production

1048 charged-current interactions with a D^0 in the final state were selected by a pattern recognition program and confirmed as neutral-particle decays through visual inspection. These data allowed a measurement of D^0 production rate and its topological branching fractions [5]. A value of:

$$\sigma(\mathrm{D}^0)/\sigma(\mathrm{CC}) = 0.0269 \pm 0.0018 \pm 0.0013\ , \tag{3.1}$$

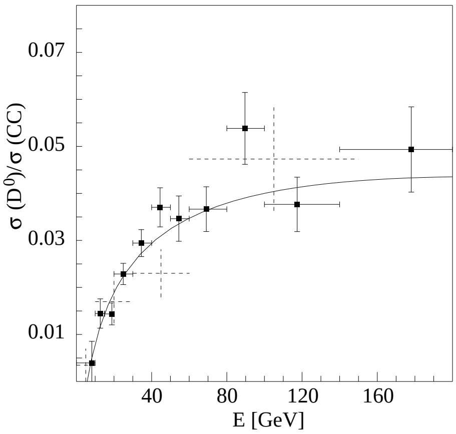

Figure 1: Energy dependence of the cross-section ratio. The data points drawn as full lines show the measurements reported here, the dashed lines the E531 [7] results. The curve through the data points shows the result of the model calculation as described in the text.

for the relative rate compared to CC is obtained. The measurement of the D^0 production rate relative to the CC interaction rate is shown as function of neutrino energy and compared with the measurement from E531 [7] in Figure 1. The energy dependence can be compared with the prediction of charm production model, by using the structure function model in Ref. [8] (GRV94LO). This parametrization includes slow rescaling [9], which is sensitive to the effective charm quark mass, m_c. A best fit value $m_c = 1.42 \pm 0.08$ GeV$/c^2$ has been found.

3.2 D^{*+} production

The identification of $D^{\star+}$ in CHORUS[6] is based on its decay into D^0 and π^+ The procedure used relies on the high purity of the sample of D^0 events recognized by the decay topology and by the low Q-value of the $D^{\star+}$ decay (corresponding to a maximum p_T of 39 MeV/c [10]). As a consequence, the π^+ from the $D^{\star+}$ decay has a relatively low momentum (<4 GeV/c) and small angle with respect to the D^0 direction. A value of

$$\frac{\sigma(D^{\star+})}{\sigma(D^0)} = 0.38 \pm 0.09(\mathrm{stat}) \pm 0.05(\mathrm{syst})\,. \tag{3.2}$$

is obtained. Combining it with D^0 production measurement one obtain

$$\frac{\sigma(D^{\star+})}{\sigma(CC)} = [1.02 \pm 0.25(\mathrm{stat}) \pm 0.15(\mathrm{syst})]\%\,. \tag{3.3}$$

3.3 Inclusive charm production

Since it is not possible to identify the charged charmed particles on an event-by-event basis, the separation among them is achieved in a statistical approach by exploiting the different lifetimes of Λ_c^+, D^+ and D_s^+, hence by loocking the flight length over charm momentum distribution. The flight length of charmed hadrons is very precisely measured in the emulsion target. The momentum of the charmed hadrons is not directly measured, but it can be estimated exploiting the correlation between the momentum and the angular distribution of the decay products. The analysis of full Chorus sample will be soon published, a preliminary value of inclusive charm cross-section relative to CC interactions

$$\sigma(\nu_\mu N \to \mu^- cX)/\sigma(\nu_\mu N \to \mu^- X) = (5.9 \pm 0.4)\% \tag{3.4}$$

has been obtained.

3.4 Measurement of muonic branching ratio of charmed hadrons

The measurement of the muonic branching ratio B_μ has been exploited by other experiments, but in these experiments B_μ is left as one of the free parameters of the fit to the dimuon data. A direct measurement is performed in CHORUS [13], based on the complete sample of 2013 manually confirmed charm events. For well identified D^0 sample has been obtained the value

$$B_\mu(D^0) = [6.5 \pm 1.2 \text{ (stat)} \pm 0.3 \text{ (syst)}] \times 10^{-2} \ ,$$

The inclusive muonic branching ratio for the complete sample of charm hadrons yields

$$B_\mu = [7.3 \pm 0.8 \text{ (stat)} \pm 0.2 \text{ (syst)}] \times 10^{-2}.$$

3.5 Charm production induced by anti-neutrinos

By requiring a positive muon charge as determined by the CHORUS muon spectrometer, 32-$\bar{\nu}_\mu$ induced charm events were observed with an estimated background of 3.2 events [14]. At an average antineutrino energy in the neutrino beam of 18 GeV, the charm production rate induced by antineutrinos is measured to be $\sigma(\bar{\nu}_\mu N \to \mu^+ \bar{c}X)/\sigma(\bar{\nu}_\mu N \to \mu^+ X) = (5.0^{+1.4}_{-0.9}(\text{stat}) \pm 0.7(\text{syst}))\%$. The charm production rate as a function of the antineutrino energy is found to be in good agreement with previous results derived from di-lepton data.

4. Charm background in future neutrino factory experiments

One of the main goals of the Neutrino Factory program would be the discovery of leptonic CP violation [11]-[12]. The most sensitive method to study this topic is the measure of the transition probability $\nu_e(\bar{\nu}_e) \to \nu_\mu(\bar{\nu}_\mu)$. This is what is called the "*golden measurement at the Neutrino Factory*" [12] At the Neutrino Factory an energetic electron neutrino beam is produced with no contamination from muon neutrinos with the same helicity (only muon neutrinos of opposite helicity are present in the beam, contrary to the case of conventional beams from pion decay). Therefore, the transition of interest can be easily measured by searching for wrong-sign muons, i.e. muons with charge opposite to that of the parent muons in the storage ring, provided the considered detector has a good muon charge identification capability. But wrong sign muons can be originated also from muonic decay of charmed hadrons induced by muon neutrinos of opposite helicity. A complementary channel proposed to be studied at future Neutrino Factory is the so called "*silver channel*" [15], namely the transition $\nu_e \to \nu_\tau$. Has been shown that the study of this channel in combination with the golden measurement can help to solve the intrinsic (θ_{13}, δ) ambiguity. At this purpose a detector capable of the τ-decay vertex recognition is needed. Given the short lifetime of

charmed particles similar to the one of τ lepton, the charm production represent the most important background source in the *silver channel measurement*.
By considering a neutrino factory flux from 50 GeV muon decay (polarizzation $P_\mu = 0$), by using the ν_μ, ν_e predicted spectrum, we expect a charm rate, normalized to CC interactions, of

$$R_c(\overline{\nu_\mu}) = (4.9 \pm 1.7)\%; \qquad R_c(\nu_e) = (5.9 \pm 0.4)\%.$$

The expected number of events from neutrino charm production can be written as

$$N_c = N_l^{CC} \times R_c(l) \times f_{C+} \times (1 - \varepsilon_{lID}) \times BR(C^+ \to l^+) \times \varepsilon_{\mu^+ID} \times (1 - \varepsilon_{charge}) \times \varepsilon_{det}$$

where N_l^{CC} is the total number of charged-current events induced by ν_l, ε_{lID} is the efficiency to identify the primary lepton, ε_{μ^+ID} is the probability to identify the muon produced at the decay vertex and to measure the charge for muons reaching the magnet spectrometer, ε_{charge} is the probability to correctly identify the charge of the daughter muon and ε_{det} is the probability to detect the charm decay. The expected number of events from anti-neutrino charm production can be written as

$$\bar{N}_c = \bar{N}_l^{CC} \times \bar{R}_c(l) \times f_{C^+} \times BR(C^- \to l^-) \times (1 - \bar{\varepsilon}_{lID}) \times \bar{\varepsilon}_{det}$$

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