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Observation of neutrino induced diffractive D_s^{*+} production and subsequent decay $D_s^{*+} \to D_s^+ \to \tau^+ \to \mu^+$

The CHORUS Collaboration

Abstract

We report on the first direct observation of a neutrino induced charged-current interaction with two subsequent decays of short-lived particles close to the interaction vertex. This rare double-kink signature in the CHORUS emulsion target is interpreted as a D_s^{*+} production followed by the decay chain $D_s^{*+} \to D_s^+\gamma, D_s^+ \to \tau^+\nu_\tau$, $\tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$. The event is characterised by small Q^2 and small four-momentum transfer squared t to the target nucleon, which indicates a diffractive production mechanism. A complete analysis of the event is presented.

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1 Introduction

The CHORUS experiment aims primarily at the observation of charged-current (CC) interactions $\nu_\tau N \to \tau^- X$ from $\nu_\mu \to \nu_\tau$ oscillation in the CERN SPS wide-band neutrino beam. It is a hybrid experiment with an emulsion target and an electronic tracking system opening the possibility to study the production and decay of short-lived particles ($c\tau \sim 100 - 300\,\mu$m) with a three dimensional spatial resolution of $\sim 1\,\mu$m. We studied a subsample of dimuon events for diffractive and deep inelastic $D_s^{(*)}$ production with low multiplicity at the primary vertex. In the selection we concentrated on the purely leptonic decay cascade $D_s \to \tau \to \mu$ that results in a clearly identifiable double decay (also called 'double-kink') signature.

Small Q^2 interactions with small four-momentum transfer squared t to the nucleon or nucleus play an important role in exploring the regime between deep inelastic scattering and diffractive processes. In particular, neutrino induced diffractive production is interesting, as there is only a small number of particles in the final state that reflect the structure of the weak current.

In this paper we report on the observation, analysis and interpretation of a candidate event for diffractive D_s^* production with a double-kink signature.

2 Experimental setup and event selection

The CHORUS detector consists of 770 kg of nuclear emulsion acting simultaneously as a neutrino target and a high resolution tracking detector, followed by scintillating fibre trackers, a hadron spectrometer, a calorimeter and a muon spectrometer for kinematic reconstruction of the final state. The detector is described in detail in [1].

During four years of data taking (1994-1997), CHORUS recorded about 840,000 CC interactions. The search for double-kink events reported in this paper, is performed on a subsample of 87,000 CC events from the 1994 exposure.

To find double-kink events from the reactions $\nu_\mu N \to \mu^- D_s^+ X$ or $\nu_\mu N \to \mu^- D_s^{*+}(\to D_s^+\gamma)X$, where $D_s^+ \to \tau^+\nu_\tau$ and $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$, neutrino interactions with two muons of opposite sign are selected. To be sensitive to $D_s^{*+} \to D_s^+\gamma$ decays, we allow only electromagnetic energy in the calorimeter and veto on hadronic showers by requiring that the energy released in the hadronic calorimeter be less than about 5 GeV.

The procedure of tracing back particle trajectories from the electronic detector into the emulsion has been described in [1]. In the emulsion, track following and vertex location are performed with automatic scanning microscopes [2] and after finding the primary vertex, the event is examined by eye for decay topologies with a double kink signature.

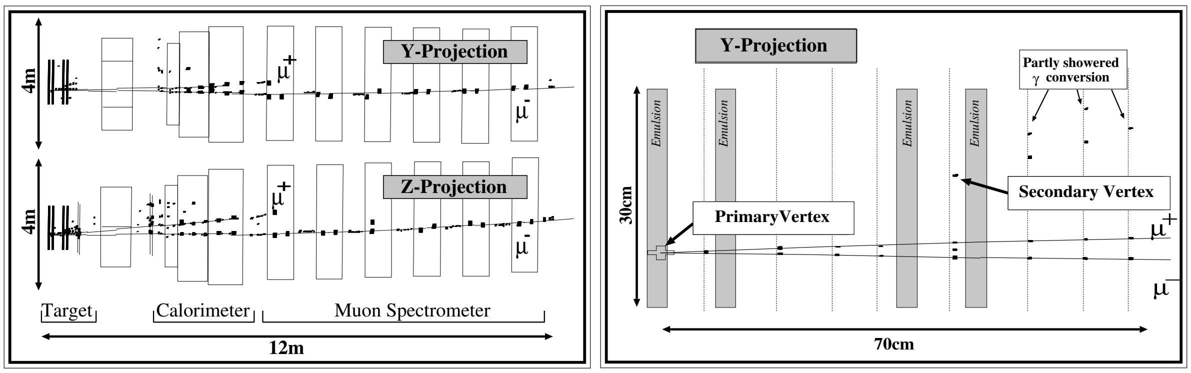
One event fulfills all the requirements of this selection.

3 Reconstruction in the detector

Figure 1 shows the detector display of the candidate event. Two identified muons of opposite sign and electromagnetic activity in the calorimeter, which can be assigned to a secondary vertex in the target region, are observed. The negative and the positive muons have measured momenta of (19.6 ± 3.9) GeV/c and (1.6 ± 0.1) GeV/c, respectively. A visible electromagnetic activity corresponding to an energy of $E_{em} = (0.27 \pm 0.09)$ GeV is detected in the calorimeter.

Further, one isolated hit shows up in a module of the hadronic calorimeter located at a distance of 380 cm away from the primary vertex, corresponding to about 1.45 interaction lengths (~ 24.5 radiation lengths). The isolated hit gives an energy signal of (0.53 ± 0.22) GeV and is probably caused by the interaction of a neutral particle, *e.g.*, the scattering of a neutron.

By following the muon trajectories into the emulsion target, a neutrino interaction vertex is found with the topology shown in Figure 2. Two tracks leave from a single grain (size $\sim 1\mu$m) without any visible charged nuclear fragment. One of these tracks matches the negative muon identified in the spectrometer, while on



(a) (b)

Figure 1: (a) Global view of the event in the detector with two identified muons of opposite sign. (b) The target area with primary and secondary vertices.

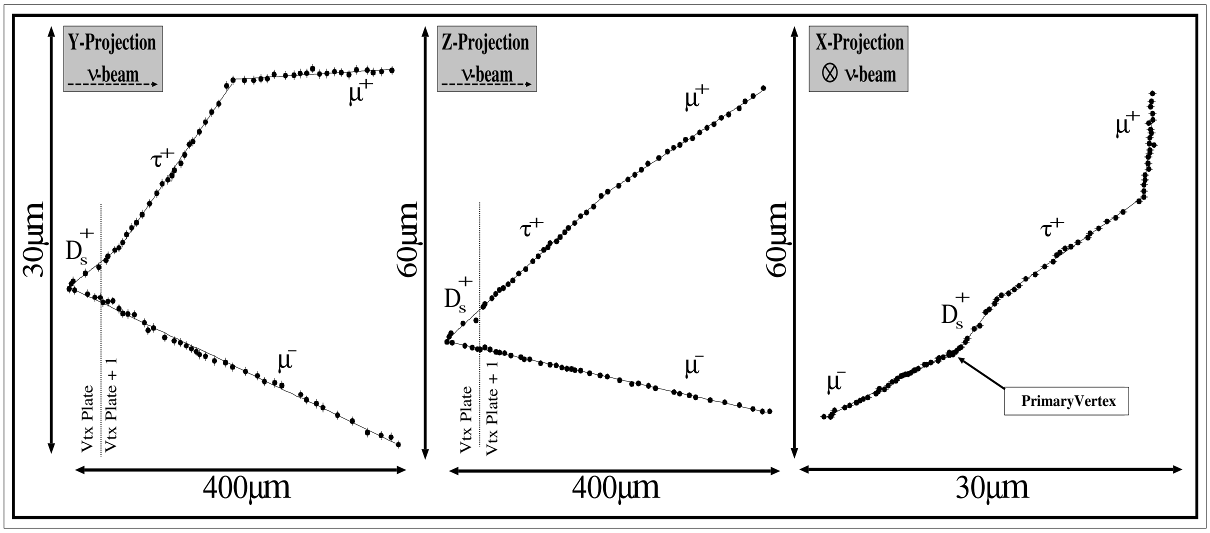


Figure 2: The double-kink event with two tracks leaving from a single grain without nuclear break-up at the primary neutrino vertex. The points are the measured position of each emulsion grain with its error. Also indicated is the borderline between two consecutive emulsion plates.

the other track (identified as positive muon in the detector) two decays are visible. After corrections for shrinkage and local distortion of the emulsion, a grain-by-grain measurement provides a three dimensional view of the vertex, tracks and decay angles. The decay angles are found to be (39.5 ± 2.4) mrad for the first and (87.3 ± 1.2) mrad for the second kink. The distance from the primary vertex to the first kink is 68 μm and that from the first to the second kink 147 μm. The first decay is located close to the surface of an emulsion plate ($\sim 16\,\mu$m distance).

4 Double-kink scenarios

In view of the measured short flight lengths, momenta and decay angles, we consider that at the primary vertex a charmed meson (D^+ or D_s^+) is produced by a neutrino. Other hypotheses are either unlikely or exotic.

Therefore, possible scenarios for the emergence of a double-kink signature are:

- A $D_s^+ \to \tau^+\nu_\tau$ and $\tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$ decay. This decay chain has already been observed in a pion emulsion exposure experiment [3].
- Elastic scattering without visible recoil ('white kink') of a D_s^+ or D^+ charmed meson and subsequent decay into $\mu^+\nu_\mu X^0$. This process has never been observed for heavy mesons and for quantitative estimates we rely on pion data [4].
- A D_s^+ or D^+ meson with subsequent decays into K^+X^0 and $K^+ \to \mu^+\nu_\mu$.

The probabilities for the different scenarios to happen and to be detected in CHORUS have been studied quantitatively with a Monte Carlo simulation of the beam, the interactions and the detector response. The nuclear emulsion target is segmented such that a double-kink signature can be detected, provided that both decays occur on average within half of an emulsion stack (14.2 mm) from the primary interaction vertex.

To calculate the number of expected events, we have taken into account detector and location efficiencies and have used the production rates described in the next section. Probabilities and expected event rates for the different scenarios are summarised in Table 1.

It can be seen that the decay chain $D_s \to \tau \to \mu$ is clearly favoured. Furthermore, the measured decay angles and momenta of the event are consistent with this hypothesis. Therefore, the most probable explanation is that the observed double kink signature originates from the decays $D_s^+ \to \tau^+\nu_\tau$ and $\tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$.

5 Production scenarios

Given that the decay of a D_s^+ is at the origin of the double kink, it is plausible that the energy measured in the electromagnetic part of the calorimeter can be associated with the conversion of a photon seen as the secondary vertex in the target region. These two observations lead to the hypothesis of a D_s^{*+} production with an immediate radiative decay $D_s^{*+} \to D_s^+\gamma$.

At the primary vertex no additional charged hadronic fragments are visible. Therefore, two conceptually different models could explain the D_s^{*+} production:

- **Deep inelastic charm production without charged fragments**
  The charm production rate per CC interaction is $(5.0^{+0.7}_{-0.6})\,\%$ [5], with a relative D_s^+ content of $(7 \pm 4)\,\%$ [6]. In a Monte Carlo simulation based

Possible double-kink scenarios	Probability for the signature within 14.2 mm	Expected number of events in 1994 data
$D_s \to \tau \to \mu$	0.96 ± 0.01	0.6 ± 0.3
$D_s \to white\ kink \to \mu$	4×10^{-3}	3×10^{-3}
$D \to white\ kink \to \mu$	4×10^{-3}	4×10^{-3}
$D_s \to K \to \mu$	$(2 \pm 2) \times 10^{-4}$	$(3 \pm 3) \times 10^{-4}$
$D \to K \to \mu$	$(9 \pm 2) \times 10^{-4}$	$(1 \pm 1) \times 10^{-4}$

Table 1: Possible scenarios to generate a double-kink signature within half of an emulsion plate (14.2 mm). Note: The 'white kink' probabilities reflect an order of magnitude estimation.

on string fragmentation models [7] adjusted to experimental data [8], we find that in at most $\sim 2\%$ of the events no other charged particles are produced at the primary vertex besides the D_s^+. In total, we expect a D_s^+ production rate of less than $7 \times 10^{-5}/CC$ from deep inelastic processes with this signature.

- **Diffractive production of a D_s^{*+} meson**
  The diffractive production mechanism for $\nu_\mu N \to \mu^- D_s^{*+} N$ is shown schematically in Figure 3. This process has been reported in [9] with a measured production rate of $(2.8 \pm 1.1) \times 10^{-3}$/CC. In charged-current interactions, the W can 'fluctuate' into a charmed meson. The D_s^{*+} production is Cabibbo favoured by a factor of $\left(\frac{V_{cs}}{V_{cd}}\right)^2 \simeq 20$ over the D^{*+} meson. The on-shell meson is produced by scattering off a nucleon or a nucleus without breaking up the recoiling partner and without changing the quantum numbers (sometimes called 'Pomeron exchange').

  Small t and small Q^2 are indicative of events described by the diffractive production model (see for instance [10]). A review of neutrino induced diffractive production of light mesons can be found in [11].

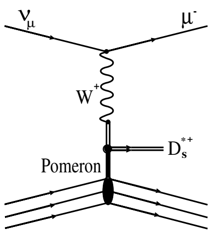


Figure 3: Diagram for neutrino induced diffractive D_s^{*+} meson production

6 Kinematic reconstruction

In addition to the μ^- and the D_s^{*+} observed at the primary vertex, we assume that a recoil neutron escapes the target nucleus and interacts in the calorimeter, leaving a visible energy of (0.53 ± 0.22) GeV. This energy deposition, the topology of the event and the kinematic constraints limit the neutron momentum to a range of about 0.7 GeV/c$\leq p_n \leq 1.8$ GeV/c. A cross-check has been performed by a full detector Monte Carlo simulation of neutrons with momenta in the same range and in $\sim 74\%$ of the events a similar signature was reconstructed.

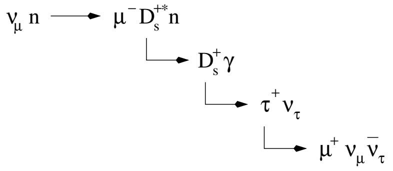
Conservation of transverse momentum at the primary vertex allows the determination of the momentum $p_{D_s^{*+}} = (1.7 \pm 0.6)$ GeV/c. Taking into account the kinematic constraints in this event, we reconstruct the neutrino energy $E_\nu = (24.9 \pm 2.2)$ GeV and the transferred momentum $Q^2 = (0.8 \pm 0.1)$ (GeV/c)^2. The assumption that the neutron is at rest before the interaction, yields a four-momentum transfer squared $t = (1.1 \pm 0.4)$ (GeV/c)^2. The Fermi motion of nucleons is small compared to the measured momentum transfer. Even if the neutron is completely neglected in the kinematic reconstruction, these values of Q^2 and t (although computed differently [11]) remain of the same order.

Given the small Q^2, the small t, the interaction of a neutral particle in the calorimeter and the absence of any visible nuclear break-up at the primary vertex, we interpret this event as diffractive production of a D_s^{*+} meson.

Because of the mass difference between D_s and τ, the two-body decay $D_s^+ \to \tau^+ \nu_\tau$ constrains the neutrino mass m_{ν_τ} even on a single event basis, depending on the observed decay angle. However, the measured decay angles in this event, although consistent with the above interpretation, do not allow to set a better limit than the one obtainable from the mass difference.

7 Summary

In this paper we have presented the observation of a neutrino induced charged-current interaction with two subsequent decays within 215μm. A complete analysis of this event is possible because of the exceptional tracking capabilities of the CHORUS hybrid emulsion detector. Topological and kinematic reconstruction for the complete event are consistent with the production and the decay chain



At the primary vertex no nuclear break-up is observed. Small $Q^2 = (0.8 \pm 0.1)$ (GeV/c)^2 and the signal of a recoil neutron ($t = (1.1 \pm 0.4)$ (GeV/c)^2) point to a diffractive D_s^{*+} production. The observation of one event is compatible with the diffractive production rate of $(2.8 \pm 1.1) \times 10^{-3}$/CC as measured in [9]

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