CERN/EP 88-51
12 April 1988

A SEARCH FOR NEUTRINO OSCILLATIONS

CHARM Collaboration

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Submitted to Zeitschrift für Physik C

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ABSTRACT

We present here the final results of experiments searching for neutrino oscillations, carried out by the CHARM Collaboration. The data-taking took place in 1983. The first experiment was performed by exposing two detectors simultaneously to the CERN PS low energy ν_μ beam. In the second experiment the full CHARM detector was exposed to the wide-band horn-focused ν_μ beam of the CERN SPS. Complete details of the experiments and data reduction are presented. No statistically significant signals for neutrino oscillations were observed. Our 90% CL limits in the appearance experiment ($\nu_\mu \rightarrow \nu_e$) exclude $\Delta m^2 \geq 0.19 \text{ eV}^2$ for complete mixing ($\sin^2 2\theta = 1$), and $\sin^2 2\theta \geq 0.008$ for the region $\Delta m^2 \geq 30 \text{ eV}^2$. These results, and the limits observed for $\nu_\mu \rightarrow \nu_x$ (disappearance of ν_μ), are in agreement with those of most other experiments but exclude part of the region previously reported as a possible indication of $\nu_\mu \rightarrow \nu_e$ oscillations.

1. INTRODUCTION

Several fundamental questions on the nature of neutrinos are still open:

- (a) Are neutrinos massive?
- (b) Are the neutrino weak interaction eigenstates identical to the mass eigenstates?
- (c) Are neutrinos identical to their antiparticles (Majorana neutrinos) or not (Dirac neutrinos)?

There are no theoretical reasons for the neutrinos to be massless. From cosmological arguments neutrinos could have a small mass, in the range of a few eV [1].

If neutrinos are massive, the weak flavour neutrino eigenstates ν_α ($\alpha = e, \mu, \tau$) are superpositions of mass eigenstates ν_i ($i = 1, 2, 3$):

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \quad (1)$$

where $U_{\alpha i}$ is a unitary mixing matrix, analog to the Cabibbo-Kobayashi-Maskawa matrix describing the flavour mixing in the quark sector. Any reaction involving the creation of neutrinos ν_α can be interpreted as an incoherent sum of all the channels i with neutrinos ν_i of kinematically allowed masses m_i with weights $|U_{\alpha i}|^2$.

The most general Lagrangian neutrino mass term can be written in matrix form:

$$\begin{aligned} \bar{\psi} M \psi &= [\bar{\psi}, \bar{\psi}_c] \begin{pmatrix} M_D & M_M \\ M_M^* & M_D \end{pmatrix} \begin{pmatrix} \psi \\ \psi_c \end{pmatrix} = \\ &= M_D \bar{\psi} \psi + M_D \bar{\psi}_c \psi_c + M_M \bar{\psi} \psi_c + M_M^* \bar{\psi}_c \psi \end{aligned} \quad (2)$$

where ψ is the Dirac neutrino field and ψ_c its charge conjugate, and M_D, M_M are the Dirac and Majorana masses. Dirac mass terms imply global lepton number L conservation, although separate lepton flavour L_α is not conserved if $U_{\alpha i}$ is not diagonal. Majorana mass terms induce lepton number violating transitions with $\Delta L = 2$.

The phenomena of mixing in the lepton sector are similar to those of the quark sector. However, the problem is experimentally much more difficult, since both the mixing matrix elements and the masses are unknown, with the additional complication that neutrinos could be Majorana particles.

Some experiments put constraints on the mass eigenstate dominantly coupled to a weak flavour neutrino eigenstate ν_α by accurately measuring the particles accompanying the neutrino, and studying their energy spectra where they are most sensitive to the neutrino mass, (i.e. close to the end-point). Tritium β -decay, π decay and τ decay have been used to study m_1 , m_2 , m_3 respectively, assuming $|\nu_e\rangle$ dominantly coupled to $|\nu_1\rangle$, $|\nu_\mu\rangle$ to $|\nu_2\rangle$, $|\nu_\tau\rangle$ to $|\nu_3\rangle$. One experiment [2,3] reported a positive result from tritium β decay: $m_\nu = 30.3^{+2}_{-9}$ eV (> 17 eV at 95% CL), which has not been confirmed by a subsequent experiment [4]. The present evidence for massive neutrinos is therefore marginal and neutrino masses may still be considered compatible with zero:

$$\begin{array}{llll} m_1 < 18 & \text{eV (95\% CL)} & [4], & m_1 > 17 \text{ eV (95\% CL) [3]} \\ m_2 < 250 & \text{keV (90\% CL)} & [5] & \\ m_3 < 50 & \text{MeV (95\% CL)} & [6] & \end{array}$$

Heavier neutrinos ν_i might still exist, with sufficiently small mixing $U_{i\alpha}$; they would manifest themselves as secondary peaks in the spectrum of the charged lepton accompanying the neutrino in leptonic meson decays like $\pi \rightarrow \mu\nu$, $\pi \rightarrow e\nu$, $K \rightarrow \mu\nu$, of intensity $|U_{i\alpha}|^2$ with respect to the primary peak corresponding to ν_α . No such peak was found up to now: limits on $|U_{i\alpha}|^2$ as functions of $m(\nu_i)$ have been set by several experiments [7].

Heavy neutrinos ν_i would also be present in beam dumps or in conventional neutrino beams produced at accelerators, with fluxes proportional to $|U_{i\alpha}|^2$. If they are heavier than about 1 MeV, they can decay in the leptonic channel $\nu_i \rightarrow e^+ e^- \nu_e$ with a rate proportional to $|U_{ie}|^2$ and can be detected. Searches of such neutrinos have been performed with negative results and have extended the limits to higher neutrino masses [8].

If neutrino masses are non-degenerate and different flavours mix, namely if $U_{\alpha i}$ is not diagonal, then direct transitions or "oscillations" [9] between neutrinos of different flavours α take place and can manifest themselves as variations in the composition of neutrino beams. Oscillations have been searched for in various beams: at reactors, at accelerators, and with atmospheric or solar neutrinos. Most results were negative, with some exceptions: one reactor experiment [10] claimed evidence for oscillations of electron antineutrinos and an experiment at an accelerator observed an excess of ν_e in a ν_μ beam [11], in contradiction with other data [12-14]. The discrepancy between the computed and measured solar neutrino flux [15] is also still to be clarified, although explanations, alternative to that of oscillations, have been put forward [16,17].

Dirac and Majorana neutrinos are distinguishable only if masses are non-zero. However, the experimental methods described above are not sensitive enough to distinguish between them. Searches for neutrinoless double β decays, allowed for massive Majorana neutrinos but forbidden for Dirac neutrinos, are the only practical experimental approach presently pursued. No such transition was found up to now, and the present limit derived for the Majorana mass term is $m_{\text{Majorana}}^\nu < 2.1 \text{ eV}$ [18].

It will be increasingly hard to improve the sensitivity of experiments designed to measure directly the neutrino masses. For non-zero but small ν masses (of the order of 1 eV or less), one of the best ways to find positive evidence may be the search for neutrino oscillations.

The CHARM Collaboration has contributed to the search for oscillations in a region of neutrino squared mass differences $\Delta m^2 \sim 0.2 \text{ eV}^2$ where contradictory results have been reported by different experiments. A first analysis of data collected in 1984 at the CERN PS low-energy muon neutrino beam gave limits for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations [19]. In the present paper, after a general discussion of the experimental method (sect. 2), and set-up (sect. 3) we describe in more detail the old muon-neutrino disappearance analysis (sect. 4), and present a new electron neutrino appearance analysis (sect. 5) which confirms our published negative results. We finally discuss a search for $\nu_\mu \rightarrow \nu_e$ oscillations in

another data sample taken with the CHARM detector in an exposure to the horn-focussed wide band neutrino beam of the CERN 400 GeV SPS, which improves our limits on the mixing angle in the region of relatively large squared mass differences ($\Delta m^2 \geq 8 \text{ eV}^2$).

2. THE EXPERIMENTAL METHOD

Neutrino mass eigenstates are stationary states which evolve with time according to

$$|v_i(t)\rangle = e^{-iE_i t} |v_i(0)\rangle, \quad (3)$$

where $E_i = (p^2 + m_i^2)^{1/2}$ is the energy and p the momentum of the neutrino. Considering for simplicity only two different neutrino flavours, for instance ν_e and ν_μ , the mixing matrix $U_{\alpha i}$ is:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix}. \quad (4)$$

As a result of the different time evolution of the two mass eigenstates, a neutrino initially in a weak eigenstate $|\nu_\mu\rangle$ has a non-zero probability to be in state $|\nu_e\rangle$ at time t :

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &= |\langle \nu_e | \nu_\mu(t) \rangle|^2 = \\ &= \sin^2 2\theta \sin^2(1.27 \frac{L}{E} \Delta m^2) \end{aligned} \quad (5)$$

where it is assumed that $p \gg m_{1,2}$, $\Delta m^2 = m_2^2 - m_1^2$ is expressed in eV^2 , the neutrino energy E is given in GeV and L is the distance, expressed in km. Conversely, the probability of finding the neutrino in the same eigenstate $|\nu_\mu\rangle$ is

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_e). \quad (6)$$

These equations describe the simplest neutrino two-flavour oscillations, in which the amplitude depends on one mixing angle θ , and the phase is proportional to Δm^2 and L , and inversely proportional to E . The oscillation length may be defined by the equation

$$\lambda = \frac{4\pi p}{\Delta m^2} = \frac{2.5p(\text{GeV})}{\Delta m^2(\text{eV}^2)} \text{ km}. \quad (7)$$

This discussion is readily generalized to three lepton flavours [20]. θ is determined in this case by 4 real parameters, three mixing angles and a phase. Expressions (5) and (6) become more complicated: probabilities are superpositions of oscillating terms whose amplitudes are functions of mixing angles and whose wavelengths are given by proper generalisations of eq. (7):

$$\lambda_{ij} = \frac{2.5p \text{ (GeV)}}{\Delta m_{ij}^2 \text{ (eV}^2\text{)}} \text{ km} \quad (8)$$

with $\Delta m_{ij}^2 = |m_i^2 - m_j^2|$. However, the first oscillation after $t = 0$ is determined by the largest difference $\Delta m_{ij}^2 = |m_i^2 - m_j^2|$, and only one oscillating term survives if one mass is much larger than the others.

The detection of a variation of the flavour composition of a neutrino beam at different distances from the source is a clear signature for oscillations of massive neutrinos. The squared mass difference Δm^2 and the mixing angle can be measured in such experiments. From eq. (5) it is clear that the ratio L/E determines the range of masses to which the experiment is sensitive. The maximum sensitivity is achieved when $E/L \sim \Delta m^2$. When $E/L \gg \Delta m^2$ the effect becomes too small to be detected. The minimum detectable Δm^2 is then given by

$$\Delta m_{\min}^2 \sin 2\theta = \frac{1}{1.27} \frac{E}{L} \sqrt{\Delta P_{\min}} \quad (9)$$

where $\Delta P_{\min}$ is the minimum probability, i.e. neutrino flux variation, detectable by the experiment.

For $E/L \ll \Delta m^2$, the finite sizes of the source, and of the detector, and the energy resolution of the detector, average out the oscillating term in eq. (5): only the amplitude, that is the mixing angle, can be measured. The minimum detectable θ in this case is:

$$\sin^2 2\theta_{\min} \sim 2 \Delta P_{\min}. \quad (10)$$

This is also the asymptotic detectable mixing angle, for large Δm^2 values.

If the experiment is dominated by statistical errors, $\Delta P_{\min} \sim N^{-1/2}$, where N is the number of detected neutrinos: increasing the statistics improves $\Delta m_{\min}^2$ very slowly ($\sim N^{-1/4}$), if E and L are fixed.

On the other hand, the sensitivity of large statistics experiments is limited by the systematic uncertainties in the knowledge of the initial flux of the neutrino beam, when one is searching for the "disappearance" of neutrinos (eq. (6)); it is limited by the possible presence of backgrounds when the "appearance" of a different flavour is searched for (eq. (5)).

These systematic uncertainties can be reduced in experiments using two similar detectors to measure the neutrino flux at two different positions simultaneously: only relative flux measurements are required, to first approximation efficiencies cancel out and backgrounds can be subtracted if one detector can be used to measure them.

In an experiment with two detectors at distances L_1 and L_2 from the source of neutrinos of energy E , optimum sensitivity is obtained when the oscillating terms are out of phase at L_1 and L_2 :

$$\Delta m_{\text{opt}}^2 = \frac{\pi}{1.27} E / |L_1 - L_2| . \quad (11)$$

In the hypothesis of full mixing ($\sin^2 2\theta = 1$) the minimum detectable Δm^2 is:

$$\Delta m_{\text{min}}^2 = \frac{1}{1.27} E \sqrt{\Delta P_{\text{min}}} / \sqrt{|L_1^2 - L_2^2|} , \quad (12)$$

where ΔP_{min} is the minimum change that the experiment can detect by comparing the normalized fluxes of the neutrinos of the dominant flavour in the two detectors.

Such a "disappearance" experiment is sensitive to any kind of possible oscillation, including unknown flavours (see sect. 4 below).

In an "appearance" experiment, if the beam initially consists of only one neutrino flavour, for instance ν_μ , the detection of another kind of neutrino, let us say ν_e , is a proof of oscillations (sect. 5). If a contamination of other neutrinos is present, or the detector suffers from backgrounds of interactions simulating the neutrino signature, one of the detectors can be used to measure these backgrounds and subtract them. The minimum detectable mass difference is in this case:

$$\Delta m_{\min}^2 \sim \frac{1}{1.27} E \Delta \sqrt{P_{\min}} / |L_1 - L_2| \quad (13)$$

The CHARM neutrino oscillation experiment performed both "disappearance" and "appearance" searches, with two similar detectors located at about $L_1 \approx 0.123$ km and $L_2 \approx 0.903$ km from the CERN PS source of neutrinos of average energy $\langle E \rangle \approx 1.5$ GeV. From eq. (11) the optimum sensitivity for the set-up of the CHARM Collaboration was approximately,

$$\Delta m_{\text{opt}}^2(\text{CHARM}) \approx 4.8 \text{ eV}^2$$

In the following sections we shall discuss the measurements of the neutrino fluxes and the limits derived for Δm^2 and $\sin^2 2\theta$.

3. THE EXPERIMENTAL SET-UP

3.1 The CERN PS neutrino beam

In 1982 a neutrino beam, dedicated to neutrino oscillation experiments, was built at the CERN Proton-Synchrotron (PS) (Fig. 1). A new 19.2 GeV proton beam was extracted from the PS. Twenty bunches of protons per spill were accelerated and ejected in fast mode every 1.2 s. The bunches, each 15 ns long, were separated in time by 105 ns. The length of a full spill, containing on average 1.2×10^{13} protons, was about 2.1 μ s.

The proton beam was directed onto a cylindrical beryllium target of 60 cm length and 8 mm diameter located at the entrance of the decay tunnel. The mean proton beam size was $4 \times 2.8 \text{ mm}^2$ with emittance of $\sim 3(\pi \text{ mm mrad})$ horizontally and $\sim 2(\pi \text{ mm mrad})$ vertically. The steering of the proton beam was controlled with the help of two pairs of detectors (split foils) - one for the up-down and the other for the left-right beam asymmetry monitoring. Two Beam Current Transformers (BCT), placed in the proton beam, measured its intensity to an accuracy of better than 1%. One was used to measure the integrated intensity in the bursts and the other in the individual bunches. Such measurements were needed for the computation of the dead time (sect. 3.3).

The length of the target, corresponding to 1.5 interaction lengths, was optimized to give a large flux of pions and kaons and at the same time small reabsorption effects for particles produced at small angles.

Most of the pions and kaons decayed in the 48 m long, 2.8 m high and about 5 m wide decay tunnel, in air at atmospheric pressure, mainly into $\mu^\pm$ and $\bar{\nu}_\mu$. A small contamination of electron (anti) neutrinos, due to the less frequent decay modes $K_L^0 \rightarrow \pi^\pm e^\mp \bar{\nu}_e$, and $K^\pm \rightarrow \pi^0 e^\pm \bar{\nu}_e$ was taken into account in the electron-neutrino appearance analysis. The decay tunnel, surrounded by earth, was followed by a 50 cm concrete wall, a 4 m long iron absorber and about 50 m of earth (Fig. 2), which absorbed the residual hadrons and most of the muons. In the decay tunnel there were some more active elements for the beam monitoring. A 1 mm thick aluminium foil was placed in the front part of the decay tunnel and was watched by a video camera. Each burst resulted in a bright spot on this foil giving an indication of the beam shape. In a gap in the iron shield that followed the decay tunnel a secondary emission foil and a set of solid state detectors monitored the muon flux.

In this beam the CHARM Collaboration recorded data corresponding to about 9.8×10^{18} protons on target.

The ideal behaviour of the neutrino beam is that of a flux coming from a pointlike source, located at the target position. In the experiment one relevant contribution to the deviation from this behaviour was due to protons not interacting in the target and showering in the end wall of the decay tunnel. A test was performed in order to measure this component of the neutrino flux. The target was taken out and $1.6 \cdot 10^{17}$ protons were ejected in the usual manner. The number of recorded events, in the time window of the spill, dropped to 17.5% of that recorded during normal data taking. This measurement was used to check the reliability of the Monte-Carlo program computing the neutrino flux. Another deviation is due to the finite lateral size of the decay tunnel. This effect and others of minor importance were studied by Monte-Carlo simulations, discussed in sect. 4.2.

3.2 The CHARM detectors

The axis of the new neutrino beam pointed towards the three existing neutrino detectors, BEBC, CDHS and CHARM, located at a distance of about 900 m, in the Neutrino Hall along the SPS neutrino beam line.

The CHARM neutrino detector has been described before [21]. It is composed of a fine-grain target calorimeter and of a muon spectrometer (Fig. 3). The target calorimeter consists of 78 marble plates of 8 cm thickness and of 3 m x 3 m cross section (total weight of about 156 t) which are interleaved between layers of scintillation counters (3 cm thick, 15 cm wide and 300 cm long), and Proportional Drift-Tubes (PDT, 3 cm x 3 cm x 400 cm). The proportional drift-tubes extend into the 45 cm wide magnetized iron frame that surrounds the marble plates. The calorimeter has been upgraded by adding in front of each of the marble target plates a plane of digital wire chambers working in the limited streamer mode [22] with a wire distance of 1 cm and covering a surface of 265 cm x 265 cm, with wires oriented at 90° with respect to those of the proportional drift tubes. The orientation of all detector elements alternates between horizontal and vertical in consecutive gaps.

This detector was built for the study of neutrino interactions in the neutrino beam of the CERN Super Proton Synchrotron (SPS). Its main features are its high efficiency for detecting showers already at low energies ($\epsilon > 99\%$ for $E_{sh} \geq 1.5$ GeV), good hadron energy resolution ($\sigma(E_h)/E_h = 0.47/\sqrt{E_h}$ [GeV] and pattern recognition capabilities allowing, for example the detection of muons with momenta as low as 1 GeV/c in charged current ν_μ events. This yields high efficiency for classifying events as charged current or neutral current interactions by direct recognition of the muon. Charged current events initiated by high energy electron-neutrinos can be recognized because of the characteristic difference in lateral profile of electron and hadron induced showers.

The response and resolution of the calorimeter to hadronic and electromagnetic showers has been measured in electron and pion beams in the energy range from 1 to 140 GeV [23]. For energies lower than 5 GeV these calibrations were performed with a special set-up at ITEP-Moscow; for higher energies the CHARM detector itself was calibrated at CERN. The energy response of the CHARM detector, defined as the ratio of the observed visible energy E_{vis} and the mean beam energy E , is shown in Fig. 4.

For the neutrino oscillation experiment the CHARM calorimeter was exposed to the low energy PS neutrino beam described in sect. 3.1. The analysis of low energy neutrino events required substantial modifications of the event reconstruction algorithms used in the higher energy experiments. These new criteria and the response of the detector at low energies are discussed in more detail in sect. 4 and 5.

For the purpose of performing a search for oscillations with two detectors simultaneously (Fig. 5), part of the CHARM calorimeter was moved closer to the neutrino source. This part of the detector is called the "Close Detector (CD)", while the rest of the detector is called the "Far Detector (FD)": the names refer to the different distances from the beam target.

The close detector consisted of 18 of the marble plates and of the associated detector elements: scintillation counters, proportional drift tubes and streamer tubes. The first scintillator plane was enlarged to cover a $4 \times 4 \text{ m}^2$ area and was used as a veto on incoming charged particles. A set of 20 non-magnetized iron plates, spaced by 15 cm (dimensions: $400 \times 400 \times 8 \text{ cm}^3$) and interleaved with planes of 128 PDTs, was installed behind the calorimetric part of the close detector. It was used as a "muon catcher" to enhance the detection efficiency of long muon tracks.

The CD and FD were both oriented at an angle of 22° to the beam direction, since the FD could not be rotated from its alignment in the high energy neutrino beam produced by the CERN SPS.

The CD fiducial target mass was about 27 t and the distance of the centre of the fiducial volume to the centre of the target was 123 m. It was displaced from the beam axis horizontally by 0.5 m.

The remaining 60 subunits of the CHARM calorimeter and the muon spectrometer formed the FD. Its fiducial mass was about 122 t. The centre of the fiducial volume was at 903 m from the target, and it was on the nominal beam axis.

3.3 The trigger and data acquisition system

Each of the two CHARM detectors had its own data acquisition computer. They were connected by a data link, and recording took place at the FD. Besides the usual information from scintillators, PDTs and streamer tubes, some additional data were included in order to unambiguously attribute events to bursts and to bunches within bursts. To be able to compute the dead times of the two detectors, at each burst we recorded also a block of data from the Neutrino Facilities Monitoring computer including the total burst and individual bunches proton intensities, as measured by the two BCTs.

The decision to initiate the digitization and the acquisition of data from the detector was made on the basis of the discriminated signals from individual scintillators. An event was accepted when a fast coincidence among hits in at least 3 scintillator planes (called H3) took place within a 20 μ s "burst-gate" that included the 2.1 μ s beam burst. The data acquisition dead time was longer than 2.1 μ s and only a single event per detector per burst could be recorded. The trigger rate was about one in 10 bursts for both detectors.

For every event the time t between the start of the burst gate and the H3 trigger signal was recorded. Due to propagation time differences in the scintillators, the precision of this measurement was about ± 10 ns. Compared to the width of a spill (15 ns) this was good enough for a dead time calculation and checks of the suppression of possible background from slow neutrons. The distribution of t , shown in Fig. 6, demonstrates the absence of such a background.

A "wide burst gate" of 20 ms duration, including the 20 μ s "burst gate", was used to record cosmic events with the same H3 trigger, and measure the background induced by cosmic rays in the two detectors (sect. 4.1).

About 100 ms after the "burst gate", a "cosmic gate" was opened for 550 ms. During this time cosmic events were recorded for calibration purposes. For these data the trigger condition was changed in such a way that long tracks were preferentially selected: Less than 2 hits in the veto plane and at least one hit in at least 3 planes with plane numbers 4, 8, 12, 16 (CD) or 20, 24, ..., 76 (FD) were required.

The total number of neutrino events recorded corresponded to 9.8×10^{18} protons on target. Only runs with both detectors alive most of the time, and no severe problems (such as magnet currents off, parts of the active detector elements not operational or unstable beam conditions) were selected for further analysis (table 1). In a second step "bad events" were discarded, these being defined as events recorded in one detector while the other was temporarily not operational. Since, as mentioned above, only one event per detector per burst could be registered, the detectors were blind for other events that occurred later in the same burst gate. Due to different rates of neutrino and background events (including cosmics) the losses caused by this deadtime were different in the two detectors. The flux-weighted deadtimes were calculated, separately for each run and each detector.

The average fractional deadtime losses of the runs weighted by their contributions to the sum of the protons on target gave the total deadtime loss of a detector. They were 1.93% and 5.68% for the FD and CD respectively, with negligible errors.

The data collected and dead times are summarized in table 1 for periods with both detectors operational.

4. THE ν_μ DISAPPEARANCE ANALYSIS

As discussed in sect. 2, one way of searching for oscillations in this experiment is to measure the muon neutrino flux in the "close" and "far" detectors, and to compare the observed fluxes with those expected in the hypothesis of no oscillations.

Neutral Current (NC) interactions have the same cross section for all flavours and cannot be used to tag the neutrino flavour. Charged Current (CC) interactions for different neutrino flavours, on the contrary, are characterized by different charged leptons in the final state and their cross sections have different thresholds, depending on the lepton masses. Most of the neutrinos in our beam had not sufficient energy to produce τ

or heavier leptons via charged current interactions. Therefore, oscillations of muon-neutrinos to the associated neutrinos of the above leptons (or to other "inert" neutrinos, i.e. right-handed singlet states) would have shown up as reduced ν_μ charged current event rates. On the other hand, charged current electron neutrino interactions clearly are kinematically possible. Their final states are characterized by the absence of a muon, replaced by an electron, and experimentally somewhat resemble neutral current interactions. Thus oscillations of muon neutrinos to any other neutrino flavour manifests itself as a reduction in the event rate of charged current events with a muon in the final state (ν_μ -disappearance).

Charged current events in both detectors were selected by a computer algorithm. The ratio of the observed rates r_{obs} in the two detectors was properly corrected for the different deadtimes, cosmic backgrounds and efficiencies (sect. 4.1), and then compared to the expected ratio r_{exp} , computed with Monte Carlo programs simulating the beam and the response of the detectors (sect. 4.2). Introducing in the computation of r_{exp} the hypothesis of oscillations characterized by the two parameters $\sin^2 2\theta$ and Δm^2 , limits on these parameters were finally derived (sect. 4.3).

The fine granularity of our detector allowed us to directly identify electromagnetic showers from electron-neutrino charged current interactions. This analysis (electron neutrino appearance) is described in chapter 5.

4.1 Observed ratio of events in the close and far detector

A computer algorithm was developed to select contained events in both detectors; in order to reject neutral-current events, criteria preferring charged current quasielastic events due to muon-neutrinos, with at most a small hadronic cascade, were introduced. A typical accepted event was characterized by a clearly visible muon track and little activity around the vertex, while neutral-current events usually have a broad shower. However, this algorithm also accepted most of the ν_e initiated CC interactions (sect. 5).

The following criteria were used to pre-select the events:

- (a) The event time was required to lie in a narrow time window around the burst.
- (b) Events with more than 5 hits in the scintillators of any single plane were rejected. Such events were supposed to be mostly of NC origin, or in a few cases disturbed by hits from noisy scintillators.
- (c) At least one scintillator hit in at least four consecutive planes, were requested, as a necessary condition to perform a track fit.
- (d) Events with two separated clusters (i.e. two groups of consecutive planes with scintillator hits) and additional isolated hits were disregarded. Such an event pattern was considered to be unusual for a CC event.

A "fit region" was defined for each of the events of this restricted sample, starting in the marble plate before the group of at least 4 consecutive scintillator planes and ending after the last scintillator plane hit. If a gap of at least two planes was found inside this region, the end was redefined to exclude the second part.

In each of the two projections separately the following criteria were then applied:

- (a) More than 2 PDT tubes with no signal between PDT hits in a plane caused the event to be disregarded. Such an event pattern is unusual for a CC event.
- (b) At least a total of 2 hits in the PDT and streamer tube system were required, to allow the reconstruction of the direction.
- (c) Events with fit region beginning in the first or the second plane both in the CD (and in the FD) or hits in the scintillators and PDTs of the second detector plane were rejected. In this way tracks entering from the front were excluded. Such events are either of cosmic origin or beam related background (e.g. muons produced by neutrino reactions in the material in front of the detector).

A track fit in each projection of these events was carried out using the position of the PDT hit with the largest pulseheight and the average streamer tube position in each plane. If there were only 3 hits (PDT and streamer tubes) in three different planes of a projection, the fit was considered to be "successful" when all fitted points were located less than ± 15 cm off the fitted line. If there were more hits one was allowed to lie outside this area. Finally events were retained if the following conditions were also met:

- (a) The track fit was "successful", in the sense explained above.
- (b) The fits in both projections matched longitudinally.
- (c) The track angle was smaller than 53° with respect to the detector axis. If the angle was larger the events were mostly entering or leaving the detectors from the sides, top or bottom.
- (d) The fitted track did not leave the detector. In this way cosmic muons entering the detector from the back and stopping in the calorimeter were excluded from the data samples. Another reason for this condition was that the muon energy could be computed by range only if the track length was known.

The event vertex was computed as the intercept of the fitted track with the starting plane of the "fit region" in the transverse directions.

The fiducial volume, for the event vertex coordinates, was restricted in the transverse directions to the marble area ($3 \times 3 \text{ m}^2$). In this way cosmic tracks entering from the sides were rejected. Since this area was fully covered by scintillators a calculation of the energy of the event could be performed. In the longitudinal direction, the allowed volume started at the third plane of each detector and ended such that tracks could have at least 4 successive planes with hits in the scintillators. In the CD, tracks entering the last marble subunit (plane 18) were treated separately to take into account the change in detector granularity from the calorimeter to the muon catcher. Thus the accepted events crossed a minimum of 4 to a maximum of 15 planes, corresponding to a muon momentum of at least 100 MeV/c and up to above 800 MeV/c. Longer events in the FD were also treated separately. 2043 events in the CD and 268 in the FD were retained by this analysis. Most of these "contained events" are quasi-elastic CC muons, including also, however, CC interactions of ν_e , as will be discussed in sect. 5.

In order to compare the event rates measured in the two detectors each event was weighted by the inverse of the probability that an event of projected length ℓ can be seen in the available number of planes. The weight factor ω for each event was

$$\begin{aligned}\omega_{FD} &= 1/(58 - \ell) && \text{(far detector)} \\ \omega_{CD} &= 1/(16 - \ell) && \text{(close detector)}\end{aligned}\tag{14}$$

where ℓ is the projected event length measured by the scintillators and expressed in number of traversed detector planes. In Fig. 7 the weighted distribution of projected lengths ℓ is shown for both detectors; the CD event distribution is scaled down by a factor 53 corresponding to the ratio of solid angles subtended by the CD and FD.

The number of observed and weighted events of fig. 7 are also given in table 2, grouped in three bins of ℓ (4-6, 7-10, 11-15). The ratio of weighted events r_{obs} , corrected for backgrounds and inefficiencies, was computed as:

$$r_{obs} = \frac{N_{FD}}{N_{CD}} \times c_{dead} \times c_{cosmic} \times c_{double}\tag{15}$$

where N_{FD} and N_{CD} are the weighted numbers of events, c_{dead} is a deadtime correction factor, c_{cosmic} is a cosmic subtraction factor, c_{double} is a correction factor taking "double events" into account.

The systematic uncertainties on the weighted event ratio were essentially due to uncertainties in the true projected length. This was estimated to be $\pm 3\%$ by varying the measured lengths by ± 0.25 planes.

The deadtime correction factor c_{dead} is the ratio of the CD and FD lifetime fractions, discussed in sect. 3.3. It is $c_{dead} = 0.96$ with negligible errors (table 2), and independent of the event length.

Since the FD was more than 3 times as long as the CD, the cosmic ray rate in the two detectors was different. Thus the correction factor was calculated in the following way: All the cuts were applied to events occurring while the 20 ms "wide burst gate" was still open and the 20 μ s

"burst-gate" already closed. The different rates of surviving events weighted as discussed above gave the correction factor $c_{\text{cosmic}} = 0.96$, averaged for tracks with a projected length of 4 to 15 planes.

Some events could not be treated correctly by the analysis program. These events, called "double events", consisted of three classes:

- (i) Real double events: Two events that happened very close in time ($\Delta t \leq 200$ ns) were recorded by the readout system as a single event. The filtering program tried to analyze them as one event and failed to perform a line fit.
- (ii) Cosmic double events: The PDT readout system had a longer sensitive time (~ 2 μ s) than the scintillator system. The hits in the proportional drift tubes of a first cosmic track, which did not fulfil the trigger conditions, in some cases had not yet been cleared from the memory when a second event, giving a scintillation trigger, occurred. In these cases, the fit algorithm could reject the event.
- (iii) Spurious hits: Electronics problems, cross-talk, or other reasons occasionally led to spurious hits, generally in the PDT system, which could cause the fit to fail.

To correct for "double events" an unbiased sample of 2511 CD and 1407 FD events, chosen at random before any event selection, were scanned by eye by two independent scanners. The scanners disregarded any "double hits" while searching for events which passed the computer code criteria. An event was called a "double event" when it would have been accepted without such extra hits.

The percentages of double events were found to be $(7.0 \pm 2.0)\%$ and $(11.3 \pm 3.1)\%$ in the far and close detectors respectively, where the errors were estimated with the help of a second scan. The correction factor applied was thus $c_{\text{double}} = 0.96 \pm 0.04$.

Events with projected length ℓ longer than 15 planes were analysed separately, because they needed a different treatment in the far and close detectors. Since the marble part of the far detector was significantly longer than that of the close detector, the fraction of events entering the FD end system was not relevant; for the CD on the contrary about 50% of the collected events entered the muon catcher. These events could not be disregarded. This was especially important for tracks longer than 15 planes, since they could not be treated by the "weight method" previously described using the projected event length as measured by scintillators in the calorimeter. As mentioned earlier, the muon catcher consisted of 20 iron slabs, each 8 cm thick, interleaved by arrays of PDTs. The average density was 3.1 times higher than the average density in the marble part of the calorimeter. Since the energy loss of muons is proportional to the density of the traversed material, the tracks passing the μ -catcher were computer "expanded" by the density ratio. This could be done using the knowledge of the track angle and the stopping point in the catcher. The expansion was done up to the point where the track would have entered the iron frame surrounding the imaginary marble slabs. In the analysis to obtain the number appearing in Table 2, the expanded tracks were treated as normal calorimeter tracks. Some of them, that stopped in the real catcher, would have left laterally the marble subunits. These were rejected. Only events with a projected length of at least 16 marble or marble-"equivalent" planes, as measured by scintillators in the calorimeters and by PDTs in the catcher, were analysed in this way. 1329 events in the CD and 45 events in the FD had a projected event length in the range of 16 to 49 planes. The total systematic uncertainty of the long track expansion method that was used for tracks in the range of 16 to 49 planes was estimated to 3.3%. The same corrections discussed previously had to be applied. They are listed in Table 2.

4.2 Computation of the expected ratio of close and far detector rates

The ratio r_{exp} of the expected number of events in the far and close detectors, assuming that no oscillation occurred, was computed with two Monte-Carlo (MC) programs. The first simulated the proton interactions and the decay processes in the decay tunnel and was used to compute the neutrino fluxes at the detectors (beam MC). The second was written to evaluate the efficiency of the detectors for neutrino interactions (detector MC).

The main aim of the simulation program describing the neutrino beam was to calculate the ratio of the neutrino fluxes at the locations of the detectors. The ratio of fluxes ϕ_F/ϕ_C is equal to $R_{CD}^2/R_{FD}^2 = 0.0187$ if the neutrino flux is isotropic (where R is the distance of the detector from the source). Deviations from this simple behaviour are due to reabsorption of pions and kaons produced at small angles in the target, to the finite lateral size of the decay tunnel and to the distribution of the decay points of pions and kaons over the length of the decay tunnel. The neutrino and antineutrino energy spectra at the far detector extracted from such calculations are shown in Fig. 8. The computed ratio of fluxes as a function of the neutrino energy is shown in Fig. 9.

The aim of the detector Monte-Carlo was to compute efficiencies for the detection of charged- and neutral-current neutrino interactions in the detectors, as functions of the neutrino energy.

Three kinds of charged-current neutrino events were generated:

- (a) Quasielastic events, i.e. $\nu + n \rightarrow \mu^- + p$, with the differential cross sections given by M. Dewit et al. [24].
- (b) Events with Δ resonance production, i.e. $\nu + N \rightarrow \mu^- + \Delta$, with the corresponding differential cross section [24], properly normalized to the known value of the plateau of the cross section [25].
- (c) Inelastic events, i.e. $\nu + N \rightarrow \mu^- + X$, which were additionally generated in such a way that the total cross section showed the correct linear dependence on the neutrino energy above 0.8 GeV [26]. The x and y distributions were taken from the Gargamelle data [27].

For a mean neutrino energy of 1.5 GeV the mixtures of these 3 channels used were 50%, 20% and 30%, respectively, in agreement with available data [28].

Similarly, NC events in the corresponding channels to the above 3 were also generated [29]. For the deep inelastic channel the values of R were taken from experiment [30].

The vertex of the events was generated in marble. The tracking of the events was done within the framework of the TATINA Monte-Carlo (MC) package [31], to simulate the CHARM detectors including the magnetic field in the frames. The generated events were processed and selected by the filtering program. The detector efficiency calculated by this method is shown in fig. 10 for events with a projected track length of 4 to 15 planes. The efficiency ϵ_{NC} for neutral current events is smaller than ϵ_{CC} for the interesting energy range $E_\nu < 2$ GeV. However, ϵ_{NC} is not zero and the contribution of neutral current events to the accepted sample slightly affects the sensitivity of the experiment. The contribution assumed in the calculation of r_{exp} is $NC/CC = 20\%$, in agreement with the existing data and an upper limit of 26% derived by comparing the observed rates with the MC predictions.

The neutrino energy spectra produced by the beam Monte Carlo and these efficiencies were combined to predict event rates. The integrated rates computed, in the hypothesis of no oscillation, are shown in Table 3 expressed in units of events per 10^{19} protons on target and per ton of detector fiducial mass. Most of the primary proton interactions, took place in the beryllium target rod, but some protons traversed it and interacted in the air of the decay tunnel or in the material at the tunnel end. The ratio of the calculated rate of events without and with target (15%) is in good agreement with the observed value (17.5%).

The total number of expected events in the far detector was approximately 240, which is in fair agreement with the observed number of 268 events (the corresponding figures for the close detector can only be compared after weighting the observed number of events). The agreement within $\sim 10\%$ of these absolute rates gives us confidence in the reliability of the Monte Carlo computation of ratios of rates, where to first order all systematic uncertainties cancel.

The systematic uncertainties in the Monte-Carlo computation of the expected ratio r_{exp} are as follows:

- (a) π , K parameterization. The primary π , K production in proton-beryllium interactions was described by a formula fitted to available p-Be data with protons from 18.8 to 24.0 GeV and secondary momenta from 1 to 18 GeV/c [32]. Varying the parameters by $\pm 1\sigma$, changed the ratio by $\pm \begin{smallmatrix} 0.1 \\ 0.7 \end{smallmatrix} \%$. If low energy data were excluded from the fit the ratio changed by -1.0%.
- (b) Target re-interactions. Taking only absorption effects into account and neglecting cascade reactions in the target changed the ratio by $\pm 0.16\%$.
- (c) Protons traversing the target. A certain number of protons interacted only behind the target in the air of the decay tunnel or in the material at the end of the tunnel. A variation of $\pm 30\%$ in the number of protons traversing the target led to a variation of $\pm 0.3\%$ in the ratio. A comparable contribution came from a similar variation of the relative normalization of the TATINA MC, which was used to compute the contribution to the neutrino flux of the interactions after the target.
- (d) Efficiencies. The efficiency curve (Fig. 10) for charged-current events was shifted by ± 0.1 GeV, resulting in a $\pm 0.7\%$ shift of the ratio. The rather flat MC efficiency curve for neutral current reactions was shifted up and down by a factor 2. This changed the ratio by $\pm \begin{smallmatrix} 0.1 \\ 0.3 \end{smallmatrix} \%$.
- (e) Folding procedures. Smoothing the efficiency, cross section and flux curves could contribute a maximum error of $\pm 0.5\%$ in the ratio when these curves were combined.

Adding these systematic errors and the statistical error of the MC calculation in quadrature, gave an error of 1.5% in the ratio r_{exp} . Adding to this error the uncertainties originating from the ratio NC/CC mentioned above, we estimate our total error on r_{exp} to be about $\pm 5\%$.

4.3 Results of the disappearance analysis

In Table 4 the observed ratios discussed in sect. 4.1 are compared with the expected ones, described in sect. 4.2, for the five ranges of projected length l used in Table 2. The last column contains the corresponding average neutrino energy. The mean neutrino energy of the full sample ($4 \leq l \leq 49$) is 1.3 GeV.

From Table 4 we conclude that for short tracks (4-15 planes) the ratio of the observed and expected event ratios in the hypothesis of no oscillations is:

$$r_{\text{obs}}/r_{\text{exp}} = 0.96 \pm 0.06 \pm 0.05 \quad (16)$$

and for long events (16-49 planes)

$$r_{\text{obs}}/r_{\text{exp}} = 1.21 \pm 0.20 \pm 0.04 \quad (17)$$

A χ^2 method was used to compare ratios of the observed event rates in the two detectors, with those expected in the hypothesis of oscillations, with parameters ($\sin^2 2\theta$, Δm^2)

$$\chi^2 = \sum_{i=1}^4 \frac{(r_{\text{exp}}(\sin^2 2\theta, \Delta m^2) - r_{\text{obs}})^2}{\sigma_i^2} \quad (18)$$

where the sum is extended to the 4 bins in projected length and $\sigma_i^2 = \sigma_{\text{obs}}^2 + (0.05 \times r_{\text{exp}})^2$. Here the second term in the sum takes into account the systematic uncertainties.

For fixed Δm^2 the value of $\sin^2 2\theta$ was varied and the resulting ratio $r_{\text{exp}}(\sin^2 2\theta, \Delta m^2)$ was computed. Then the values of $\sin^2 2\theta$ corresponding to a one sided 90% confidence level, namely those for which $\Delta\chi^2 \equiv \chi^2(\Delta m^2, \sin^2 2\theta) - \chi_{\text{min}}^2 \geq 1.64$, were determined. This was repeated stepwise for all values of Δm^2 , yielding the region within which this experiment can exclude $\nu_\mu \leftrightarrow \nu_\tau$ -oscillations. The result is shown in Fig. 11.

The most sensitive limit for the mass difference is $\Delta m^2 \leq 0.29 \text{ eV}^2$ for complete mixing and the most sensitive value for the mixing angle is $\sin^2 2\theta = 0.17$. The effect on the sensitivity of the experiment of the NC contamination of the sample discussed above, is small. Variations from a

20% to a 30% neutral current contribution change the lower limit on Δm^2 by less than 3%. The possible presence of ν_e charged current interactions due to $\nu_\mu \leftrightarrow \nu_e$ oscillations in this sample was excluded by the analysis described in the following chapter.

5. THE ν_e APPEARANCE ANALYSIS

The CHARM fine grained calorimeter could detect and identify electromagnetic showers down to ~ 0.5 GeV. Therefore, we searched for the appearance of electron neutrino charged current interactions in the CHARM close and far detectors, monitoring the neutrino flux with the muon neutrino charged current interactions.

The samples of 2043 and 268 contained events of length $l \leq 15$ planes, selected for the disappearance analysis, were contaminated by those NC events, which had a narrow shower compatible with the selection criteria. Electron neutrino quasi-elastic interactions, characterized by narrow electromagnetic showers, would also have been mostly accepted by these criteria. A first search for the appearance of electron neutrino interactions, by visually scanning the above samples, was therefore performed and published [19]. The dash-dotted line of fig. 16 was obtained as a 90% CL limit (old analysis) for Δm^2 and $\sin^2 2\theta$.

A new analysis, discussed in this paper, was completely based on computer algorithms.

We selected a sample of mainly quasi-elastic events, characterized both for muon and electron neutrinos by just one detectable minimum ionizing particle (the charged lepton) emerging from the event vertex (sect. 5.1).

The subsample in which a muon could not be identified was mainly caused by neutral current interactions with only one charged pion visible in the detector. We searched for quasi-elastic electron-neutrino candidates in this subsample by estimators tuned to identify electromagnetic showers with the help of low energy electron and pion test data (sects 5.2 and 5.3).

After subtracting the known backgrounds from hadronic showers, and from the contamination of electron neutrinos coming from K decays, and after correcting for efficiencies, we computed the observed ratios r_{CD} and r_{FD} of electron to muon neutrino quasi-elastic charged-current events in the close and far detector respectively. Finally we derived from r_{CD} and r_{FD} limits on the parameters $\sin^2 2\theta$, Δm^2 for $\nu_\mu \rightarrow \nu_e$ oscillations (sect. 5.3).

5.1 Selection of quasi-elastic event candidates

The algorithms and programs used in this analysis are different from those described in sect. 4 (disappearance analysis).

A first set of selection criteria, aimed at reducing the contamination of cosmic ray and beam-related backgrounds, are similar to those described in sect. 4.1.

- (i) The recorded event time was required to fall within the 2.1 μs beam burst.
- (ii) Events showing activity in all the first four scintillator planes of each detector were assumed to be caused by cosmic rays or by neutrino events in the material in front of the detectors, and were disregarded.
- (iii) Events that had less than three contiguous planes with hits in the scintillators were considered as "noise" and rejected.

The events satisfying these criteria were analyzed by a vertex finding algorithm. The lateral vertex position was computed using the standard CHARM procedure for the reconstruction of the shower vertex [33]. The algorithm for the computation of the longitudinal vertex position was adapted to the specific configurations of low energy events, after extensive studies of low energy test-beam data and of EGS Monte-Carlo data.

- (iv) Events were further analyzed only if their reconstructed vertex position was transversally within ± 120 cm from the centre of the detector in both directions, that is well inside the detector in a region completely covered by the streamer tube system. Most cosmic ray tracks traversing the detector were rejected by this requirement.

After reducing backgrounds by criteria (i-iv), we restricted our sample to events with little hadronic activity close to the reconstructed vertex, that is mostly to quasi-elastic events. To this end, three cuts were applied:

- (a) No more than two neighbouring hits were allowed in the PDT's following the marble slab, in which the interaction was deduced to have happened from the position of the reconstructed vertex.
- (b) The same condition was imposed in the first streamer tube plane after the vertex.
- (c) One single hit was required in the subsequent scintillator plane.

The numbers of CD and FD events satisfying criteria (i-iv) and (a-c) are listed in Table 5.

The pattern recognition program at this point checked the events for visible muons. It was tuned to identify short muon tracks traversing a minimum of four planes well separated from other detector signals indicating possible showers. Therefore it was sensitive to muons with a minimum energy of 350 MeV. Events, for which a muon pointing towards the vertex could be reconstructed, were called " 1μ " events and were considered as candidates for charged current muon neutrino quasi-elastic events. The others were called " 0μ " (muonless events).

Electromagnetic showers, which are signatures of electron neutrino charged current events were looked for in the " 0μ " subsample. The subsample was mainly due to muon neutrino neutral current interactions with one or more detectable pions emerging from the interaction point. A fraction of these events is known to be caused by neutral pions decaying into photon pairs, each of which may produce an electromagnetic shower with two initial charged particles (i.e. a positron-electron pair).

In the electron search, to reduce the NC background, two further cuts were introduced.

- (d) Only events that deposited an energy E_{first} larger than 3.6 MeV and smaller than 8 MeV in the first scintillator after the vertex were accepted. A lower energy deposition was considered as "noise", corresponding to a wrong vertex reconstruction. On the other hand, a single electron deposits in the first scintillator an energy corresponding to only one minimum ionizing particle (6 MeV) in about half of the cases, whereas the photons from π^0 decay produce pairs of electrons and positrons, which deposit an energy corresponding to more than two minimum ionizing particles.
- (e) Finally, only events with a deposited energy of at least 600 MeV, corresponding to a visible energy in the scintillators of about 10 minimum ionizing particle hits, were considered for further analysis, since the uncertainties in the classification criteria increased below this value.

In Table 5 also the number of events satisfying criteria (d)-(e) are reported, separately for "1 μ " and "0 μ " events. Finally, 1309 quasi-elastic muon neutrino charged current candidates were identified in the close detector and 134 in the far detector; 124 and 15 muonless ("0 μ ") events satisfied the same criteria (d)-(e) and were scrutinized for an electron signature.

5.2 Electromagnetic shower identification in the CHARM calorimeter at low energies

A special effort was made to extend the knowledge of the response and pattern recognition capabilities of the CHARM detector at low energies. To this end we studied calibration data taken in electron and pion beams, with a special set-up at ITEP with beam momenta from 0.5 to 6 GeV/c and with part of the CHARM calorimeter at CERN with beam momenta from 5 to 140 GeV/c [23].

At ITEP in Moscow a small version of the CHARM calorimeter was built. It had the same structure described in sect. 3.2, but was limited in transverse dimensions to $1 \times 1 \text{ m}^2$ and longitudinally to ten modules,

each including a layer of streamer tubes, a layer of scintillators, a marble slab, and a layer of proportional drift tubes. The test beam line was equipped with two analyzing magnets and the momentum spread was $\pm 1\%$. A 3 m long threshold Cherenkov counter, filled with CO_2 , was installed in the beam to separate electrons (positrons) from hadrons.

At CERN in 1979 and 1981 thirty-six fully equipped modules of the CHARM calorimeter were exposed to a test beam of negative pions and electrons to measure the energy response and resolution for both hadronic and electromagnetic cascades, the angular resolution in the determination of the shower direction, and to develop methods for the separation of the two types of showers [23]. The beam was produced by the interactions of 200 GeV protons from the Super Proton Synchrotron (SPS). The pion beam was produced on a 150 mm long beryllium target, with a lead plate one radiation length thick to purify the hadron beam. For the electron beam an aluminium target, 100 mm long, was chosen, to increase the electron yield. A 20 m long Cherenkov counter filled with helium was placed in the beam. Particle identification was obtained by a combination of the Cherenkov information and of the measured width of the shower in the CHARM calorimeter.

After detailed studies of these test data, and using also a simulation of the detector in the framework of the EGS Monte-Carlo program, two estimators for the identification of electromagnetic showers at low energies were defined. They were based on the scintillators and on the streamer tubes respectively.

5.2.1 The "scintillator estimator" X_{sc}

The distribution of energy depositions E_{sc} in scintillators, expressed in minimum ionizing particles (MIPs), is shown in Fig. 12(a) for electrons of 0.5 GeV. There is a clear peak corresponding to scintillators traversed by one minimum ionizing particle, with a long tail due to scintillators traversed by several particles, in the core of the shower. The peak at low E_{sc} (< 0.6 MIPs ~ 3.6 MeV) is present both in the ITEP data and in the EGS simulated data, and can be removed in the Monte-Carlo by switching off the Compton scattering of photons in the scintillators. This process is clearly identified as the origin of these small energy depositions.

In Fig. 12(b) the E_{sc} distribution for electrons of 0.5 GeV is compared to that of pions of the same energy. In the distribution for pions the Compton scattering enhancement is reduced; the peak centred at 1 MIP is higher, and the tail at larger pulse heights is depressed, indicating a broader distribution for the hadron shower energy.

A "scintillator estimator" X_{sc} was thus defined for each event as:

$$X_{sc} = k \frac{n_1}{n_c} \quad (19)$$

where: n_1 is the number of "1 MIP hits" in the event, that is the number of scintillators with a p.h. from 0.8 to 1.8 MIPs (4.9 to 11.0 MeV); n_c is the number of "Compton hits", that is energy depositions smaller than 0.6 MIPs (3.6 MeV), and k is an energy dependent normalization factor, chosen to make X_{sc} energy-independent and distributed around 1 for electrons.

In Fig. 13 the average values of X_{sc} for electrons and pions are shown as functions of the beam energy. The error bars indicate the r.m.s. widths of the distributions.

5.2.2 The "streamer tube estimator" X_{ST}

Another discriminating tool was provided by the hits in streamer tubes, the smallest ($1 \times 1 \text{ cm}^2$) active detector elements in our calorimeter.

At low energies, the number of streamer tube hits for a given visible energy was smaller for hadronic than for electromagnetic cascades. The former involved a small number of rather well separated hadronic tracks, depositing relatively large amounts of energy at their stopping points, but leaving only few hits in streamer tubes. The latter on the contrary were characterized by a larger number of minimum ionizing electron and positron tracks, giving a larger number of streamer tube hits for the same visible energy. Above about 7.5 GeV the situation changed, due to the fact that overlapping tracks and hits in the core of electromagnetic showers became important.

A "streamer tube estimator" X_{ST} could therefore be defined as:

$$X_{ST} = k' \frac{n_{ST}}{E} \quad (20)$$

where n_{ST} is the number of streamer tube hits, E is the calibrated visible energy, and k' an energy dependent normalization factor.

The average values and r.m.s. widths of the distributions of this estimator for electrons and pions are shown in Fig. 14 as functions of the beam energy.

The two estimators X_{SC} and X_{ST} did not show any strong correlation (Fig. 15): they could therefore be simply combined. To identify an electromagnetic cascade candidate we required $X_{SC} < 1.5$ and $X_{ST} > 0.75$. The two estimators are plotted in fig. 15 for electrons (a), pions (b), muons (c), from ITEP test data at 1 GeV/c. The selection criteria on the combined estimators have an efficiency of about 60% for electrons, 14% for pions and 4% for muons: this gives an indication of the background which can be expected if these estimators are used to search for electrons in our muonless event sample (sect. 5.1). Since higher energy test data and Monte-Carlo interpolations for intermediate energies showed no energy dependence, in the following analysis of the muonless event sample $\epsilon_{\pi}^{estim.} = (13.9 \pm 2.2)\%$, measured with 0.5 GeV/c and 1 GeV/c pion test data was used.

5.3 Search for quasi-elastic electron neutrino event candidates

The estimators, discussed in sect. 5.2, were used to search for quasi-elastic electron neutrino charged current candidates in the samples of 124 muonless events (close detector) and 15 muonless events (far detector), selected by the analysis described in sect. 5.1 and summarized in Table 5.

In Fig. 15(d) the distribution of the estimators X_{SC} , X_{ST} for the 124 muonless events in the close detector is shown: $N_{ec}^{CD} = 17 \pm 4.1$ events are accepted as electromagnetic shower candidates; similarly $N_{ec}^{FD} = 1^{+2.3}_{-1}$ events are accepted in the far detector.

We expect these few candidates to be dominated by backgrounds. Let us consider in detail the close detector, dropping the CD superscript for simplicity in the following equations.

From our simulation of the neutrino beam we expect a small contamination of electron neutrinos from K decay. The number of electron-neutrino charged currents in the "0 μ " sample can be computed as:

$$N_{1e} = N_{1\mu} \frac{\phi(\nu_e)}{\phi(\nu_\mu)} \cdot \frac{\epsilon_e^{QE}}{\epsilon_\mu^{QE}} \quad (23)$$

where $\phi(\nu_e)$, $\phi(\nu_\mu)$ are the integrated neutrino fluxes, and ϵ_μ^{QE} , ϵ_e^{QE} are the efficiencies of all selection criteria (i)-(iv), (a)-(d) described in sect. 5.1, for muon and electron neutrino events respectively; $N_{1\mu}$ is the number of muon candidates found, as discussed in sect. 5.2 (see also table 5).

We estimate the contamination of electron neutrinos to be:

$$\frac{\phi(\nu_e)}{\phi(\nu_\mu)} = 0.007 \pm 0.002 \quad (24)$$

The ratio of the efficiencies ϵ_μ^{QE} and ϵ_e^{QE} was estimated by a Monte-Carlo simulation. For both neutrino flavours and with the proper neutrino energy spectra quasi-elastic and N, Δ resonance production reactions were generated, using the ISOBAR program for intranuclear cascade simulation [34]. All particles leaving the target nucleus were tracked through the CHARM detector, treating all electromagnetic components by the EGS program. Particles were tracked down to momenta as low as 1 MeV/c; any smaller amount of energy was deposited locally. The absolute efficiencies $\epsilon_{e,\mu}^{QE}$ of all selection criteria producing our "quasi-elastic" sample were computed. The mean efficiency for the detection of electron neutrinos was $(62 \pm 5)\%$ of the efficiency for detecting muon neutrinos; in other terms:

$$\frac{\epsilon_e^{QE}}{\epsilon_\mu^{QE}} = 0.62 \pm 0.05 \quad (25)$$

The expected number of electron neutrino interactions ("1e") in our "0 μ " sample is then, from eq. (23):

$$N_{1e} = 5.7 \pm 1.8 \quad (26)$$

If there are no oscillations, the 118 muonless events, remaining after subtracting the 5.7 events contributed by background electron neutrinos, are originated by neutral current interactions. At the low energies of interest in our case, the detectable particles in the final state are: one nucleon (elastic scattering), accompanied by one pion (N, Δ resonance production), or one or two pions (inelastic reactions). The nucleon is absorbed before reaching an active detector element or deposits a large (higher than minimum ionizing) amount of energy close to the vertex; neutral pions or pairs of charged pions are mostly rejected by selection criteria (d) discussed in sect. 5.1. As a consequence, we expect these events to behave as single charged pions in our detector. Using the results on Monte-Carlo and test data of sect. 5.2, we can estimate the hadronic background contribution to the N_{ec} candidates accepted by our estimators:

$$N_{hb} = (N_{0\mu} - N_{1e}) \cdot \epsilon_{\pi}^{estim} = 16.4 \pm 2.8 \quad (27)$$

Similarly, we obtain a number

$$N_{eb} = N_{1e} \epsilon_e^{estim} \quad (28)$$

of background events N_{eb} from the contamination of electron neutrinos in the N_{ec} candidates selected by our two estimators, where ϵ_e^{estim} is their efficiency to find electron-neutrino quasi-elastic charged current candidates in the muonless "0 μ " sample.

The efficiency ϵ_e^{estim} was computed using the Monte-Carlo simulation discussed above and was found to be $(60 \pm 5)\%$ on a sample of events selected with the "quasi-elastic" cuts (i)-(iv) and (a)-(d). No energy dependence was found in the range of neutrino energies from 0.6 to 5 GeV. This number was compatible with the fraction of single electrons accepted in ITEP electron test data at 0.5 and 1 GeV/c, as described in sect. 5.2 (Fig. 15). As a result,

$$N_{eb} = 3.4 \pm 1.1 \text{ events} \quad (29)$$

are the expected background from electron neutrinos, originating from K decays, in the muonless events accepted by our estimators.

For the close detector we finally obtain, after subtracting both backgrounds,

$$N_e^{CD} = N_{ec}^{CD} - (N_{eb}^{CD} + N_{hb}^{CD}) = -2.8 \pm 5.1 \quad (30)$$

This analysis is summarized in Table 6. It was repeated for the far detector events, yielding:

$$N_e^{FD} = -1.5 \begin{matrix} + 2.3 \\ - 1.1 \end{matrix} \quad (31)$$

The ratio r of electron neutrinos (excluded those from K decays) and muon neutrinos traversing each detector can be computed as:

$$r = \frac{N_e}{N_{1\mu}} \cdot \frac{\epsilon_{\mu}^{QE}}{\epsilon_e^{QE}} \cdot \frac{1}{\epsilon_e^{estim}} \cdot b \quad (32)$$

where all event rates and efficiencies were already defined; the correction factor $b = 1.015 \pm 0.005$ takes into account the small contamination of single charged pions (punch-through) from neutral current reactions in the sample of " 1μ " events.

All efficiencies are equal for both close and far detector and the cosmic ray background, affecting the two detectors in different ways, is negligible after the selection criteria (i)-(iv) of sect. 5.1 (as can be seen from Fig. 6). The ratios r_{CD} and r_{FD} are obtained from eq. (32) using the quoted values of efficiencies and correction factors:

$$\begin{aligned} r_{CD} &= (-0.5 \pm 1.1)\% \\ r_{FD} &= (-3.1 \pm \begin{matrix} 4.8 \\ 2.2 \end{matrix})\% \end{aligned} \quad (33)$$

where the errors are both statistical and systematic.

For small values of Δm^2 an oscillation could have occurred only during the long flight to the far detector. Therefore the measurement at the close detector could be used to subtract residual backgrounds. By assuming equal systematic errors in both detectors the difference ($r_{FD} - r_{CD}$)

implies that no more than 3.7% (90% c.l.) of the muon-neutrinos initially constituting the beam oscillated to electron-neutrinos on their way to the far detector.

For higher values of Δm^2 an oscillation could take place on the short way to the close detector and a measurement at the far detector could show just a washed-out effect. In this case, where the close detector measurement had to be considered separately, systematic uncertainties did not cancel. They were mostly due to the stated uncertainties in the efficiency calculations and amounted to $\pm 7\%$. Adding this in quadrature to the statistical uncertainty one can state that no more than 1.4% (90% c.l.) of the muon-neutrinos oscillated to electron-neutrinos during their flight to the close detector.

The results can be best presented on the Δm^2 vs. $\sin^2 2\theta$ plot ("exclusion plot"), where some regions of Δm^2 and $\sin^2 2\theta$ are excluded. This was calculated with the help of a Monte-Carlo program. The neutrino spectra were taken from the calculations leading to fig. 8 and the cross section for quasi-elastic events was computed for all energies above 0.6 GeV following a model by Llewellyn Smith [35]. All kinematically allowed values of Q^2 were taken into account and the lower detection threshold for muons and electrons was assumed to be 350 MeV.

The energy distribution of the events in the detectors was calculated by folding the neutrino spectrum with the cross section. The change of these spectra due to neutrino oscillations with all possible values of $\sin^2 2\theta$ and Δm^2 was calculated using the following formula:

$$\sum_E \phi_R(E) = \sum_E \phi_O(E) \times \sin^2 2\theta \sin^2(1.27 R/E\Delta m^2), \quad (34)$$

where $\phi_R(E)$ denotes the accepted spectra at distance R from the source to the detector ($R_{FD} = 0.903$ km, $R_{CD} = 0.123$ km) and E the neutrino energy. In this way all values of $\sin^2 2\theta$ and Δm^2 yielding differences of the integrated accepted spectra larger than the measured 3.7% could be calculated. In order to take systematic uncertainties in this method of calculating the exclusion plot into account, the measured value was increased by 5%. The excluded area (at the 90% confidence level) is shown in Fig. 16.

Above a certain value of Δm^2 the oscillation length becomes comparable to the distance between the close detector and the source. Here the close detector measurement alone gives a more significant limit in terms of the mixing angle (see dotted line in Fig. 16).

5.4 Search for electron-neutrino appearance in ν_μ WBB data

Another data sample taken with the CHARM detector was analyzed using similar procedures. It was recorded in 1983 when the detector was exposed to the horn-focused wide band neutrino beam (WBB) of the CERN 400 GeV Super-Proton-Synchrotron (SPS). The total integrated fluxes were 1.2×10^{18} and 2.3×10^{18} protons on target in the neutrino and antineutrino beams, respectively [36]. The main purpose of this data taking period was a new measurement of the ratio of the cross sections of ν_μ and $\bar{\nu}_\mu$ scattering on electrons. This experiment could also, however, be analyzed searching for $\nu_\mu \rightarrow \nu_e$ oscillations. As in the case of the analysis just described any appearance of an unexpected number of electro-magnetic showers could be interpreted as an indication for such an oscillation. With the help of formula (9) the sensitivity can be estimated. The limit on Δm^2 cannot be much better than 1 eV^2 for full mixing (distance source-detector $\sim 820 \text{ m}$, mean neutrino energy $\sim 13 \text{ GeV}$).

In contrast to the low energy data, here the mean event energy was in the region of maximum sensitivity of the CHARM detector, concerning pattern recognition, angular resolution, etc. Therefore more efficient separation cuts could be applied. The events had to fulfil the following criteria:

- (a) The vertex had to lie inside the fiducial volume, which had a cross section of $230 \times 230 \text{ cm}^2$ and covered the first 57 subunits in length.
- (b) The shower energy had to be in the range from 10 to 30 GeV.
- (c) Less than 4 of the 6 scintillator planes could be hit in the end system. At these energies about 70% of the $\bar{\nu}_\mu$ -events could be rejected in this way. This simple geometrical criterion did not affect any electron-neutrino-induced event.
- (d) The lateral shower profile observed by the streamer tubes in the first 8 planes of the event could have a limited amount of gaps ("holicity" algorithm for electromagnetic shower recognition [23]).

- (e) The density of the energy deposition in the case of electromagnetic showers is much higher than in hadronic cascades. Therefore the width Γ of the energy distribution, as deposited in the scintillators and projected onto a plane perpendicular to the shower axis, was a good separator. The root mean square, σ_{st} , of the distribution of the streamer tube hits projected onto a plane perpendicular to the shower axis was also sensitive to the different kinds of tails of hadronic and electromagnetic showers. Suitable cuts on the two estimators Γ and σ_{st} yielded a hadron shower rejection factor larger than 100, with an efficiency of $(80 \pm 5)\%$ when applied to electron test data.

In order to use the ν_e -candidate criteria derived from electron test data a restriction to QuasiElastic (QE) events with low hadronic activity was necessary. The same restrictions were applied to the candidates for muon-neutrino induced events. The corresponding cuts were based on the active elements in the first plane after the vertex, which was considered to lie in the centre of a marble plate:

- (a) The energy E_j , deposited in the first scintillator plane, had to be less than 50 MeV, corresponding to less than 7 minimum ionizing particle tracks.
- (b) Just one hit in the proportional drift tubes behind the marble plate was allowed.
- (c) No more than 6 hits, with less than 3 gaps in between, were allowed in the first streamer tube plane.

The efficiency of these cuts was $(50 \pm 11)\%$.

After applying the kinematic constraint $0.12 \text{ GeV}^2 \leq E^2 \theta^2 \leq 0.54 \text{ GeV}^2$ (where θ is the shower angle with respect to the beam axis) to reject background events from $\nu_\mu e$ elastic scattering, concentrated at low $E^2 \theta^2$, the origin of the electromagnetic activity in the remaining events still had to be determined. In order to separate ν_e -induced electromagnetic showers from others with a decaying π^0 at the origin, a cut in the visible energy on the first scintillator plane ($E_{\text{first}} < 8 \text{ MeV}$) was applied. Its efficiency was $(26 \pm 6)\%$. With all the above cuts

$$\begin{aligned} N_{\nu_e}^* &= 12 \pm 3.5 \\ N_{\bar{\nu}_e}^* &= 16 \pm 4 \end{aligned} \quad (35)$$

events were selected in the ν and $\bar{\nu}$ beam exposures respectively. Taking the above mentioned 3 efficiencies into account (10.5% in total) these numbers became:

$$\begin{aligned} N_{\nu_e} &= 115 \pm 47 \\ N_{\bar{\nu}_e} &= 152 \pm 62 \end{aligned} \quad (36)$$

These numbers had to be compared to the numbers of ν_μ -induced quasi-elastic events. The latter were selected by applying the same kinematic cuts as described previously, but taking the different resolutions into account. A special selection cut that was required in this case was the energy deposition of less than 92 MeV in the first six scintillator planes. The total efficiency, calculated by Monte-Carlo methods was about:

$$\epsilon_{\nu_\mu} \sim 0.70 \quad (37)$$

The corrected numbers of QE muon events corresponding to the above QE electron events thus become

$$\begin{aligned} N_{\nu_\mu} &= 16700 \\ N_{\bar{\nu}_\mu} &= 24000 \end{aligned} \quad (38)$$

for the same data sample and fiducial volume.

Due to a beam contamination originating from K_{e3} decays, some background of ν_e -induced events was expected. It was calculated using the beam simulation program NUBEAM [37], yielding a kaon-to-pion ratio of $(6.5 \pm 1.2)\%$. In consequence, the estimated ratio of the energy weighted fluxes of electron-to-muon neutrinos in the energy range 10 to 30 GeV was $(0.52 \pm 0.1)\%$. Thus, the expected numbers of electron-(anti)neutrino-induced events were

$$\begin{aligned} N_{\nu_e}^{\text{exp}} &= 87 \pm 17 \\ N_{\bar{\nu}_e}^{\text{exp}} &= 125 \pm 26 . \end{aligned} \tag{39}$$

Combining neutrino and antineutrino data and comparing the expected with the measured number showed an excess of 55 ± 84 events in the data sample, which cannot be interpreted as a significant indication for neutrino oscillations. It was concluded that a maximum $163/41000 = 0.4\%$ (90% c.l.) of the original muon-neutrinos oscillated to electron-neutrinos.

The excluded area in the Δm^2 - $\sin^2 2\theta$ plane, shown in Fig. 16, was calculated as described in sect. 5.3.

In conclusion, the result of the search for an oscillation $\nu_\mu \rightarrow \nu_e$, which was performed in similar ways on two different data samples, was combined in terms of an exclusion plot for various values of Δm^2 and $\sin^2 2\theta$, which is shown in Fig. 16. The combined experiment had its highest sensitivity for small mixing angles ($\sin^2 2\theta = 0.005$) at a difference of the squared masses of about 30 eV^2 . A maximum sensitivity for the mass difference of $\Delta m^2 = 0.19 \text{ eV}^2$ was achieved for full mixing. In the region of $\Delta m^2 > 30 \text{ eV}^2$, all values of $\sin^2 2\theta$ above 0.008 are also excluded.

6. DISCUSSION OF THE RESULTS

The results of our muon neutrino disappearance and electron neutrino appearance searches are summarized in Figs 17 and 18 respectively, together with results from other recent experiments [12-14,38-43]. It must be noted that the electron neutrino appearance analysis presented here gives limits similar to those obtained in the already published one in the low Δm^2 region, while it gives a better sensitivity in the larger Δm^2 region. Also, it excludes part of the $\Delta m^2 - \sin^2 2\theta$ region, in which experiment PS191 [14] reported indications of $\nu_\mu - \nu_e$ oscillations (fig. 18).

Acknowledgements

We are grateful to G. Acquistapace, A. Ball, D. Dumollard, R. Gerst, R. Guerin, R. Grüb, P. Lazeyras, J.M. Maugain, S. Rangod, D. Simon and J. Zaslavsky for the construction, the installation and the smooth running of the beam. We are very indebted to our technical collaborators G. Basti, G. DiNunzio, R. Donnet, M. Ferrat, S. Guerra, B. Friend, N. Kalganov, A. King, J. Schütt and P. Veneroni for their competent work which made this experiment possible. We gratefully acknowledge the work of J.C. Catin for the technical preparation of the pit, A. Issenbeck and H. Isch for providing a rectifier and for help in its operation. The full support of Professor Shevchenko (ITEP) for the construction of the muon ranger is gratefully acknowledged.

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TABLE CAPTIONS

- TABLE 1 Summary of data taken with good beam conditions and both detectors operational.
- TABLE 2 Observed and weighted events and ratios of close and far detector weighted and corrected events, as a function of projected event length.
- TABLE 3 Computed event rates in units of events/(10^{19} POT x ton), assuming no oscillations.
- TABLE 4 Comparison of the observed and computed event ratios in bins of projected track length.
- TABLE 5 Quasi-elastic candidates selection for the new ν_e appearance analysis (see sect. 5.1 for details).
- TABLE 6 Background subtraction for the ν_e appearance analysis and the final results.

TABLE 1

Total number of protons on target	7.76×10^{18}
Total number of triggers in FD	60968
Total number of triggers in CD	87522
Deadtime losses of FD	1.93%
Deadtime losses of CD	5.68%

TABLE 2

Proj. event length (No. of plates)	Events				Correction factors			Corrected observed weighted ratio r_{obs} (FD/CD)
	FD		CD		Cosmic subtr.	Dead- time	Double tracks	
	Observed	Weighted (N_{FD})	Observed	Weighted (N_{CD})				
4- 6	78	1.49	840	79.5	0.968	0.96	0.96 ± 0.04	0.0166
7-10	118	2.36	952	124.6	0.964	0.96	0.96 ± 0.04	0.0167
11-15	72	1.61	251	77.4	0.947	0.96	0.96 ± 0.04	0.0181
4-15	268	5.45	2043	281.4	0.961	0.96	0.96 ± 0.04	0.0171
16-49	45	28.2	1329	1330	0.985	0.96	1.07 ± 0.10	0.0215

TABLE 3

Effective target	Close detector			Far detector		
	v	$\bar{v}$	$v + \bar{v}$	v	$\bar{v}$	$\bar{v} + \bar{v}$
Target	104.0	18.4	122.4	1.88	0.33	2.21
Air + end of tunnel	3.0	0.5	3.5	0.03	0.01	0.04
Target + air + end of tunnel	107.0	18.9	125.9	1.91	0.34	2.25
No target in	16.1	3.0	19.1	-	-	-

TABLE 4

Proj. event length	Observed ratio	MC ratio	Final result	$\langle E_{\nu CC} \rangle$ [GeV]
	$r_{\text{obs}} \pm \text{stat. err.}$	r_{exp}	$r_{\text{obs}}/r_{\text{exp}} \pm \text{stat. err.}$	
4- 6	0.0166 ± 0.0019	0.0174	0.95 ± 0.11	1.14
7-10	0.0167 ± 0.0016	0.0177	0.94 ± 0.09	1.26
11-15	0.0181 ± 0.0020	0.0182	0.99 ± 0.11	1.30
	$r_{\text{obs}} \pm \text{stat.} \pm \text{syst.}$	$r_{\text{exp}} \pm \text{syst.}$	$r_{\text{obs}}/r_{\text{exp}} \pm \text{stat.} \pm \text{syst.}$	
4-15	$0.0171 \pm 0.0010 \pm 0.0009$	0.0178 ± 0.0003	$0.96 \pm 0.06 \pm 0.05$	1.24
16-49	$0.0215 \pm 0.0036 \pm 0.0007$	0.0177 ± 0.0003	$1.21 \pm 0.20 \pm 0.04$	1.76

TABLE 5

Selection	CD		FD	
Total triggers	96065		66687	
Events remaining after cuts:				
In time (i)	76178		10353	
Entering tracks (ii)	44363		9187	
Minimum lengths (iii)	37388		8543	
Fiducial volume (iv)	14048		1715	
Quasi-elastic (a)	8191		1082	
selection (b)	6102		790	
(c)	4787		634	
	1 μ	0 μ	1 μ	0 μ
3.6 < E_f < 8 MeV (d)	1606	277	161	32
$E_{\text{vis}} < 600$ MeV (e)	1309	124	134	15

TABLE 6

	CD	FD
$N_{1\mu}$	1309 ± 36	134 ± 12
$N_{0\mu}$	124 ± 11	15 ± 3.9
N_{ec}	17 ± 4.1	$1 \pm_{-1}^{2.3}$
N_{eb}	3.4 ± 1.1	0.58 ± 0.17
N_{hb}	16.4 ± 2.8	1.96 ± 0.32
N_e	-2.8 ± 5.1	$-1.5 \pm_{-1.1}^{2.3}$
r (%)	$(-0.5 \pm 1.1)\%$	$(-3.1 \pm_{-2.2}^{4.8})\%$

FIGURE CAPTIONS

- Fig. 1 The CERN Proton-Synchrotron (PS) neutrino beamline dedicated to neutrino oscillation searches.
- Fig. 2 The layout of the CERN PS neutrino beam.
- Fig. 3 The CHARM neutrino detector.
- Fig. 4 The energy response of the CHARM detector, both for hadronic and electromagnetic cascades. Measurements made at CERN are indicated by squares and circles, whereas the results of the ITEP measurements are represented by black squares.
- Fig. 5 The Close and Far CHARM Detectors layout.
- Fig. 6 The distribution of the time t between the start of the burst gate and the event trigger signal for events accepted as charged current muon neutrino events in the appearance analysis: (a) close detector; (b) far detector.
- Fig. 7 Weighted distributions of the projected lengths. C: close detector, scaled down by a factor 53; F: far detector; MC: Monte-Carlo.
- Fig. 8 The neutrino energy spectra at the far detector as calculated by the beam Monte-Carlo (see text).
- Fig. 9 Ratio of neutrino fluxes at the close and far detectors as a function of the neutrino energy. The dashed line indicates the expected geometric ratio from a point source (see text).
- Fig. 10 The efficiencies for charged- (CC) and neutral-current (NC) interactions as calculated by the detector Monte-Carlo program.
- Fig. 11 Limits on a neutrino oscillation $\nu_{\mu} \leftrightarrow \nu_x$ from the CHARM muon neutrino disappearance analysis (see text for the detailed method of the limit calculations).

FIGURE CAPTIONS (Cont'd)

- Fig. 12 The distribution of energy depositions, per scintillator, E_{sc} , in MIP units: (a) Electrons: test data and simulated data at 0.5 GeV. The dashed curve represents the simulated data without Compton scattering. (b) The distribution for both electrons and pions from ITEP test data at 0.5 GeV.
- Fig. 13 The scintillator estimator as a function of energy. The error bars indicate the r.m.s. of the distributions.
- Fig. 14 The streamer tube estimator as a function of calibrated visible energy. It is normalized to about 1 for electron showers. The error bars indicate the r.m.s. width of the distributions.
- Fig. 15 Distribution of the streamer tube (X_{ST}), vs. the scintillator (X_{SC}) estimators for 1 GeV ITEP test data: (a) electrons, (b) pions and (c) muons. The area chosen to identify the ν_e -candidates is indicated. (d) The same for the "0 μ " 124 oscillation run events in the close detector.
- Fig. 16 The parameters of $\nu_\mu \leftrightarrow \nu_e$ oscillations excluded by this experiment. The full line is the limit extracted from possible oscillations from the close to the far detector, the dotted line indicates the limit extracted from possible oscillations between the source and the close detector and the dashed line originates from the oscillation analysis of the wide band beam data. The dash-dotted line shows the published results [20] of the first CHARM analysis.
- Fig. 17 Compilation of experimental results for $\nu_\mu \leftrightarrow X$ and $\nu_\mu \leftrightarrow \nu_\tau$ oscillations: experiment E531 [38], CCFR Collaboration [39], CDHS Collaboration [40], IMB experiment [41]; CHARM collaboration (this experiment).
- Fig. 18 Compilation of experimental results for $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_e \leftrightarrow X$ oscillations: BNL [12], Los Alamos [42], E531 [38], BEBC Collaboration [13], PS191 [14], Bugey [10], Gösgen [43].

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