A SEARCH FOR OSCILLATIONS OF MUON NEUTRINOS
IN AN EXPERIMENT WITH $L/E \approx 0.7$ km/GeV

CHARM Collaboration

F.Bergsma, J.Dorenbosch, M.Jonker¹⁾, and C.Nieuwenhuis
NIKHEF, Amsterdam, The Netherlands

J.V.Allaby, U.Amaldi, G.Barbiellini²⁾, L.Barone,
A.Capone, Y. Eisenberg³⁾, W.Flegel, L.Lanceri, M.Metcalf, J.Panman,
D. Perret-Gallix⁴⁾, R. Plunkett, C. Santoni, F. Vannucci⁵⁾ and K. Winter
CERN, Geneva, Switzerland

I.Abt, J.Asplazu, F.W.Büsser, H.Daumann, P.D.Gall, T.Hebbeker,
F.Niebergall, P.Schütt, and P.Stähelin

II. Institut für Experimentalphysik⁶⁾, Universität Hamburg, Hamburg, Germany

P.Gorbunov, E.Grigoriev, V.Kaftanov, V.Khovansky and A.Rosanol
Institute for Theoretical and Experimental Physics, Moscow, USSR

A.Baroncelli⁷⁾, B.Borgia⁸⁾, C.Bosio⁷⁾, M.Diemoz⁸⁾, U.Dore⁸⁾, F.Ferroni⁸⁾,
E.Longo⁸⁾, L.Luminari⁸⁾, P.Monacelli⁸⁾, F. de Notaristefani⁸⁾,
L.Tortora⁷⁾ and E.Valente⁸⁾
Istituto Nazionale di Fisica Nucleare, Rome, Italy

(Submitted to Physics Letters B)

¹⁾ Now at SLAC, Stanford, USA

²⁾ On leave of absence from INFN, LN Frascati, Italy.

³⁾ On leave of absence from Weizmann Institute, Rehovoth, Israel.

⁴⁾ LAPP, Annecy-le-Vieux, France.

⁵⁾ LPNHE, Univ. Pierre et Marie Curie, Paris, France.

⁶⁾ Supported by Bundesministerium für Forschung und Technologie, Bonn, German Federal Republic.

⁷⁾ INFN Sezione Sanità and Istituto Superiore di Sanità, Rome, Italy.

⁸⁾ Dipartimento di Fisica, Università "La Sapienza", Roma and INFN Sezione di Roma, Rome, Italy.

ABSTRACT

A low-energy muon neutrino beam was used to illuminate two similar fine-grained neutrino detectors placed at 123 m and 903 m from the beginning of the neutrino source. The fiducial masses of the "close" and the "far" detector were about 36 tons and 120 tons respectively. The average energy of the selected neutrino events was 1.5 GeV. Data were recorded for an integrated flux of about 10^{19} protons. Events initiated by ν_e 's have been searched for and an upper limit of 2.7%, at 90% confidence level, is obtained for the fraction of ν_μ 's transformed into ν_e 's. For complete mixing this corresponds to a limit $\Delta m^2 \leq 0.20 \text{ eV}^2$ for the transition $\nu_\mu \rightarrow \nu_e$ and to a minimum value of the mixing parameter $\sin^2 2\theta = 0.04$. In the same data sample oscillations of ν_μ 's to ν_τ 's, and possibly heavier neutrinos, do not appear. For complete mixing the limit in this case is $\Delta m^2 \leq 0.29 \text{ eV}^2$.

The notion of neutrino oscillations put forward by Pontecorvo [1] has recently been the subject of many experimental searches. Such searches can be divided into two categories: a) experiments based on the comparison of a computed neutrino flux with the flux measured by one detector placed at a suitable distance from the source; b) experiments in which the neutrino flux is measured by two detectors running simultaneously at different distances from the source. Two-detector experiments running simultaneously have the great advantage of not needing an absolute normalization of the neutrino flux. Each kind of search can be further characterized as a "disappearance" or as an "appearance" experiment. In the first case, one looks for an anomalous variation of the flux of neutrinos of a certain flavour with distance. In the second, the appearance of neutrinos of a flavour initially not present in the beam is searched for. Until recently various experiments of the one-detector type have put limits on the disappearance of $\nu_e(\bar{\nu}_e)$'s [2], on the appearance of $\nu_e(\bar{\nu}_e)$'s in $\nu_\mu(\bar{\nu}_\mu)$ -beams [3], on the appearance of $\nu_\tau(\bar{\nu}_\tau)$'s in $\nu_\mu(\bar{\nu}_\mu)$ -beams [4] and on the appearance of $\bar{\nu}_\mu$'s in ν_e -beams [5]. One experiment has been performed by placing a single detector at two distances from the core of a nuclear power reactor to search for the disappearance of $\bar{\nu}_e$'s [6]. In spring 1983 two new searches of the two-detector type were carried out in a specially built low-energy ν_μ -beam at the CERN Proton Synchrotron (PS), by the CERN-Dortmund-Heidelberg-Saclay Collaboration and by the CERN-Hamburg-Amsterdam-Rome-Moscow Collaboration. In the present paper we describe the results of the search performed by the CHARM Collaboration by simultaneously looking with two detectors for both the appearance of ν_e 's and the disappearance of ν_μ 's. This is the first report of an appearance experiment which uses two detectors.

A proton beam of energy 19.2 GeV was extracted from the CERN Proton Synchrotron (PS) and focussed onto a cylindrical beryllium target of 60 cm length and 8 mm diameter. Each PS spill lasted 2.2 μ s and contained approximately 1.2×10^{13} protons; data were recorded for a total of 9.8×10^{18} protons. Pions and kaons produced in the target were allowed to decay in a tunnel, immediately following the target, of 48 m length, 2.8 m height, and approximately 5 m width. It was surrounded by earth, and terminated by a concrete wall (50 cm thick), an iron absorber (4 m thick) and earth. The ν_μ and $\bar{\nu}_\mu$ spectra calculated by Monte Carlo methods are shown in the insert of Fig. 1. The contamination of $\nu_e(\bar{\nu}_e)$'s is estimated to be $\leq 0.5\%$.

The CHARM fine-grained calorimeter has been described in several previous publications [7]. It consists of 78 subunits each consisting of a layer of 20

scintillator counters, a layer of 256 streamer tubes, a marble plate and a layer of 128 proportional drift tubes (PDT's), oriented parallel to the streamer tubes. The marble plates have dimensions of 300 x 300 cm², and a thickness of 8 cm, and they are surrounded by an iron frame which is 45 cm wide and is instrumented with PDT's only.

For the neutrino oscillation search, the first 18 subunits of the calorimeter were detached from the main detector and installed at an average distance of 123 m from the beryllium target. This apparatus will be referred to as the "close" detector. The remaining 60 subunits were centered at a distance of 903 m from the target, and are referred to as the "far" detector. The close detector was backed up by 20 non-magnetized iron plates of 4 x 4 m² surface and 8 cm thickness interleaved with planes of PDT's. This "muon catcher" followed the calorimeter modules and enhanced the efficiency for the containment of long muon tracks. The close detector had a fiducial target mass of approximately 36 tons, the far detector had 120 tons. The close and far detectors were both oriented at an angle of 22° to the beam direction, since the far detector could not be rotated from its alignment in the high energy neutrino beam produced by the CERN SPS. The layout of the close and far detectors in the PS neutrino beam is sketched in Fig. 1. The average ratio of the solid angles subtended by a subunit of the two detectors was:

$$\Delta\Omega_F/\Delta\Omega_C = (123/903)^2 = 0.0186 . \quad (1)$$

An event was accepted when a fast coincidence among any three scintillator planes took place during a 20 μ s gate which included the 2.2 μ s beam spill. On average one event was recorded in 10 spills. The present analysis has been restricted to data taken while both detectors were operational, corresponding to 7.8×10^{18} protons striking the target.

The insert of Fig. 1 shows that the beam contained mainly muon neutrinos. Under the assumption that the muon-neutrino is a linear combination of only two mass eigenstates, the probability that a ν_μ of energy E (in GeV) appears as a ν_e at a distance L (in km) from the source is:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E) , \quad (2)$$

where Δm^2 (in eV²) is the absolute value of the difference of the masses squared of the two relevant mass eigenstates and θ is the corresponding mixing angle. The ν_e appearance experiment aims at setting limits on the parameters

Δm^2 and $\sin^2 2\theta$ appearing in Eq. (2). In the disappearance experiment the probability that a ν_μ remains a ν_μ is investigated:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E) , \quad (3)$$

The parameters Δm^2 and $\sin^2 2\theta$ have in this case a different meaning from the parameters appearing in Eq.(2) because they refer to transitions of muon-neutrinos to any other neutrino flavours.

These equations show that the ratio L/E is a figure of merit for a neutrinos oscillation search. For this reason the analysis concentrated on a subsample of low energy events which have their vertex in the marble and are fully contained in the marble and in the iron frame surrounding it. To put limits on the parameters of Eq. (2), the excellent pattern recognition properties of the detector have been used to search for the appearance in the far detector of quasielastic charged-current events initiated by electron-neutrinos. These events are characterized by relatively short and narrow electromagnetic showers whose selection is almost unaffected by the containment requirement. In this case the average neutrino energy was $E(\nu_e) \approx 2.2$ GeV. Because of the containment condition all events with tracks leaving the detector (mainly muons) were rejected, with the result that the average energy of the charged current events initiated by muon-neutrinos was $E(\nu_\mu) \approx 1.3$ GeV, and the sensitivity of the disappearance experiment (eq.(3)) to a small mass difference was enhanced.

Events were selected by a computer algorithm which aimed at detecting charged current quasielastic events such that (i) in the electron-neutrino case, the scintillator and tube hits formed a compact shower with few hits at the vertex; (ii) in the muon-neutrino case, there was a clear track stopping in the detector and little activity at the vertex. The algorithm was based on three criteria:

1. At least four contiguous scintillator planes were hit.
2. A good fit of a straight line to the average position of the hits in each PDT layer and in each streamer tube layer was required; from this line and the scintillator information a starting and an end point and a length ℓ (in number of subunits) were reconstructed for each event.

3. The length had to be $\ell \leq 15$ subunits and the starting and end points had to be compatible with an interaction vertex in marble and a stop in marble or the surrounding iron.

Additional fiducial volume conditions (15 subunits in the close detector and 57 subunits in the far) and track angle limits were introduced to improve the rejection of background events due to traversing cosmic rays and beam-related entering muons. The algorithm rejected complicated events containing several prongs and/or a diffused shower, but (unavoidably) retained neutral current events characterized by a compact shower. A Monte Carlo simulation based on existing bubble chamber results, gave a fraction of 20% neutral current events in the range $4 \leq \ell \leq 15$. In the final computation of the limiting values of the oscillation parameters this value was assumed.

The computer algorithm selected 2043 events in the close detector and 270 events in the far detector. The Monte Carlo simulation predicted ~ 220 events in the far detector, in good agreement with the observed number. To search for the appearance of quasielastic ν_e interactions, the 270 events in the far detector and 850 events out of the 2043 events of the close detector were eye-scanned to search for electromagnetic showers. Events were accepted as candidates if:

1. The length was $\ell \geq 5$ subunits and the pulse height in the scintillator layers reached the maximum value at least 3 subunits after the vertex.
2. The sum of the scintillator pulse heights in the 2nd, 3rd and 4th subunits from the vertex was larger than that of 9 minimum ionizing particles (mip).
3. The pulse height in the last scintillator layer of the event was smaller than 3 mip.

Using these criteria 66 (19) electron candidates were observed in the close (far) detector. The raw energy distribution of these events is shown in Fig. 2a. The measured average shower energy in the close detector is (1.65 ± 0.2) GeV.

From an analysis of the quasielastic ν_e events generated by the Monte Carlo program mentioned above, it was established that, with the computer

algorithm described above, the ratio of the efficiencies for selecting charged-current ν_e -events with respect to ν_μ -events was (2.25 ± 0.1) . This ratio is larger than 1 because charged-current ν_μ -events are frequently rejected by the containment conditions. The same Monte Carlo events were used to determine the absolute efficiency of the scanning criteria used to find ν_e charged current events: $(45 \pm 5)\%$. Thus the overall efficiency for finding ν_e induced charged current events was $(100 \pm 12)\%$ of the efficiency for finding ν_μ charged current events. After correcting for these efficiencies and for the effect of the different lengths of the detectors (7%), the ratios between events attributed to ν_e and ν_μ charged current events were found to be:

$$\begin{aligned} \text{close detector : } R_C &= (\nu_e/\nu_\mu)_C = (9.2 \pm 1.1 \pm 1.1)\% \\ \text{far detector : } R_F &= (\nu_e/\nu_\mu)_F = (8.9 \pm 2.0 \pm 1.0)\% . \end{aligned} \quad (4)$$

The first errors are statistical and the second ones take into account the systematic uncertainties on the efficiencies of the selection procedure and are strongly correlated in the close and the far detector. The ratios R_C and R_F are larger than the fraction of ν_e 's in the beam ($\leq 0.5\%$) because the final sample is contaminated by neutral current events, but by computing the difference $(R_F - R_C)$ one can state that, with a 90% confidence level, no more than 2.7% of the ν_μ 's initially constituting the beam transform into ν_e 's. By making use of Eq.(2) and by using a maximum likelihood method to take into account the energy spectrum of the neutrinos and the energy dependence of the efficiencies for detecting ν_μ 's and ν_e 's, the continuous curve of Fig. 3a was obtained. For complete mixing the limit obtained is:

$$\nu_\mu \rightarrow \nu_e : \Delta m^2 \leq 0.20 \text{ eV}^2 \quad (\sin^2 2\theta = 1, 90\% \text{ C.L.}) . \quad (5)$$

By varying within large limits the efficiency for detecting ν_e -events computed by the Monte Carlo simulation, it was checked that this limit varies by less than $\pm 0.02 \text{ eV}^2$. The best limit for the mixing angle is obtained for $\Delta m^2 \approx 2 \text{ eV}^2$: $\sin^2 2\theta < 0.04$ (90% C.L.).

The samples of 2043 events contained in the 15 subunits fiducial volume of the close detector and of 270 events contained in the 57 subunits fiducial volume of the far detector were also used to search for muon-neutrino disappearance. This analysis was based on the comparison of the ratio r_{obs} of the neutrino event rates observed in the far detector and in the close

detector with the expected ratio r_{exp} . This ratio is very close to the ratio of the solid angles given in Eq.(1) and was calculated by a Monte Carlo convolution of neutrino fluxes, detection efficiencies and cross sections. The quantity $r_{\text{obs}}/r_{\text{exp}}$ is expected to be very close to one in the absence of oscillations.

The ratio r_{obs} can be expressed in terms of the observed rates and of two correction factors, after subtraction of the background:

$$r_{\text{obs}} = (1-d_C)/(1-d_F) \cdot (1-D_C)/(1-D_F) \cdot (N_F/N_C) \quad (6)$$

The subscripts C,F refer to the close and the far detector quantities respectively. The various quantities entering into Eq.(6) are discussed in the following paragraph; they represent the fractions d_C and d_F of "double" events lost in the analysis, the fractional dead times D_C and D_F of the two detectors and the number of observed events N_F and N_C .

Events having either spurious hits in PDT's or in streamer tubes or an unassociated second track, may occur with different probabilities in the close and in the far detector and are often discarded by the computer selection algorithm. They were therefore rejected and the relative event losses had to be corrected for. To this end an unbiased sample of 2511 close detector and 1407 far detector triggers, chosen at random before any event selection, was visually scanned. The fractions of "double" events found were $d_C = (11.3 \pm 3.1)\%$ and $d_F = (7.0 \pm 2.0)\%$. The different trigger rates of the two detectors cause different dead times which must be corrected for; from beam monitoring information it was found that $D_F = 1.9\%$ and $D_C = 5.7\%$, with negligible errors. The numbers of neutrino induced events N_C and N_F per subunit were obtained by taking into account the different fiducial length of the close detector (15 subunits) and far detector (57 subunits). Since the close detector is much shorter than the far one, to compare the length distributions the events were weighted inversely proportional to the number of target plates available for the vertex. For events with length ℓ the weights are $1/(58-\ell)$ and $1/(16-\ell)$ for the far and the close detector, respectively. The weighted distributions are compared in Fig. 2b for $4 \leq \ell \leq 15$. They are compatible within the errors and are well represented by the results of the Monte Carlo calculation.

After subtraction of a 3.4% cosmic ray background in the far detector (determined by counting events in a gate delayed with respect to the neutrino burst) the ratio of the integrals of the distributions is:

$$N_F/N_C = 0.0186 \pm 0.0010 \pm 0.0006 \quad (7)$$

where the first error is statistical and the second one (3%) is an estimate of the systematic error due to uncertainties in the ℓ -determination.

After applying the correction factors of Eq.(6), the observed ratio of the rates per unit mass in the two detectors becomes:

$$r_{\text{obs}} = 0.0171 \pm 0.0010 \pm 0.0009 , \quad (8)$$

where the errors on d_C and d_F have been included in the systematic error.

The expected ratio of rates per unit mass is given by ratio of the solid angles (1), corrected for the effect of the length and of the finite transverse dimensions of the decay tunnel and for the detector efficiencies. The correction was computed by a Monte Carlo program which describes the production and reinteraction of pions and kaons and the interactions of the protons which are not absorbed in the target with the air and the end wall of the tunnel. The expected ratio is:

$$r_{\text{exp}} = (0.96 \pm .015) (\Delta\Omega_C/\Delta\Omega_F) = 0.0178 \pm 0.0003 , \quad (9)$$

where the error has been obtained by estimating the effect of changing the parameters appearing in the Monte Carlo program. Finally, the ratio sensitive to oscillation is:

$$r_{\text{obs}}/r_{\text{exp}} = 0.96 \pm 0.06 \pm 0.05 , \quad (4 \leq \ell \leq 15) . \quad (10)$$

The 270 events observed in the far detector were further subdivided into three subsamples of different projected lengths; the corresponding ratios are plotted in Fig. 4. The fourth point appearing in the figure was obtained by considering far detector events with muon tracks longer than 15 subunits and correspondingly events in the close detector having a muon stopping in the muon-ranger. The event length in the muon-ranger of the close detector was expanded by the ratio of the density of iron to marble modules ($= 3.1$). After applying corrections similar to the ones discussed above, the ratio for the longest tracks is:

$$r_{\text{obs}}/r_{\text{exp}} = 1.21 \pm 0.20 \pm 0.04 \quad (16 \leq \ell \leq 49) . \quad (11)$$

The results plotted in Fig. 4 are compatible with the absence of muon neutrino oscillations along the flight path of the present experiment. To express them in terms of the parameters Δm^2 and $\sin^2 2\theta$ appearing in Eq.(3), it was assumed that the $\nu_\mu(\bar{\nu}_\mu)$'s neutrinos which oscillated do not produce charged current events with a muon in the detector and that all neutrinos have the same neutral current cross-section. This is legitimate, since (i) $\nu_\mu \rightarrow \nu_e$ oscillations are excluded to a very high accuracy by the results discussed above; (ii) ν_τ 's of this low energy (~ 1.5 GeV) and neutrinos associated with heavier not yet discovered charged leptons do not produce charged current events. For full mixing ($\sin^2 2\theta = 1$) the limit given by the present experiment is

$$\nu_\mu \rightarrow \nu_X : \Delta m^2 \leq 0.29 \text{ eV}^2 \text{ (}\sin^2 2\theta = 1, 90\% \text{ C.L.)} \quad (12)$$

It has been checked that this limit changes by less than ± 0.01 when varying by 50% the fraction (20%) of neutral current events which the Monte Carlo predicts to be present in the final sample.

In conclusion, the appearance of a neutrino flavour initially not present in the beam has been studied for the first time in a two-detector experiment. The result on the appearance $\nu_\mu \rightarrow \nu_e$, plotted as a continuous curve in Fig. 3a, improves on the existing limits for small mixing angles in the mass range $0.8 \leq \Delta m^2 \leq 3.5 \text{ eV}^2$. As far as the search for ν_μ -disappearance is concerned, the curves of figure 3b show that our results are in agreement with the limit obtained by the CDHS Collaboration [11], and that both give an improvement by an order of magnitude on the previous experiments in the small Δm^2 region.

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, V. Gemanov, 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 Prof. Shevchenko (ITEP) for the construction of the muon ranger is gratefully acknowledged.

REFERENCES

1. B. Pontecorvo, Zh. Eksp. Teor. Fiz. 34 (1958) 247
[Sov. Phys. JETP 7 (1958) 172].
B. Pontecorvo, Zh. Eksp. Teor. Fiz. 53 (1967) 1725
[Sov. Phys. JETP 26 (1968) 984].
2. F. Reines et al., Phys. Rev. Lett. 45 (1980) 1307.
F. Boehm et al., Phys. Lett. 97B (1980) 310.
H. Kwon et al., Phys. Rev. D24 (1981) 1097.
H. Deden et al., Phys. Lett. 98B (1981) 310.
O. Erriquez et al., Phys. Lett. 102B (1981) 73.
3. J. Blietschau et al., Nucl. Phys. B133 (1978) 205.
N. Armenise et al., Phys. Lett. 100B (1981) 182.
N.J. Baker et al., Phys.Rev.Lett. 47 (1981) 1576.
G.N. Taylor et al, Phys.Rev. D28 (1983) 2705.
P. Nemethy et al., Phys. Rev. D23 (1981) 262.
4. N. Armenise et al., ref. 3.
A.E. Asratyan et al., Phys. Lett. 105B (1981) 301.
N. Ushida et al., Phys. Rev. Lett. 47 (1981) 1694.
G.N. Taylor et al., ref.3.
C. Haber et al., Fermilab. preprint, FERMILAB-CONF-83/57-Exp. (1983).
5. A.M. Cooper et al., Phys. Lett. 112B (1982) 97.
6. Caltech-SIN-TUM Collaboration, J.L. Vuilleumier et al., Phys. Lett. 114B (1982) 298.
7. A.N. Diddens et al., CHARM Collaboration, Nucl. Instr. and Methods 176 (1980) 189.
A.N. Diddens et al., CHARM Collaboration, Nucl. Instr. & Meth. 178 (1980) 27.
M. Jonker et al., CHARM Collaboration, Phys. Scr. 23 (1981) 677-679.
8. F. Dydak et al., CDHS Collaboration, Phys. Lett. B134 (1984) 281.

FIGURE CAPTIONS

- Fig. 1: Sketch of the neutrino beam derived from the CERN Proton-Synchrotron and the close and far CHARM detectors. The insert shows the computed ν_μ and $\bar{\nu}_\mu$ fluxes at the far detector.
- Fig. 2: (a) Observed distributions of the electron energies of ν_e candidates in the close and in the far detector.
 (b) Distribution of the length ℓ (in number of subunits) of ν_μ events selected in the close and far detector. The number of events in each bin is corrected for the effective fiducial mass and normalised to the far detector solid angle. The dotted line indicates the Monte Carlo prediction, normalised to the total number of events observed in the close detector.
- Fig. 3: (a) The 90% confidence limit obtained in the appearance experiment $\nu_\mu \rightarrow \nu_e$ is compared with the best previously obtained limits for oscillations of the types: $\nu_\mu \rightarrow \nu_e$ (Baker et al., ref. 3) and $\bar{\nu}_e \rightarrow \bar{\nu}_x$ (J.L. Vuilleumier et al., ref. 6).
 (b) the 90% confidence limit obtained in the disappearance experiment is compared with previous limits on ν_μ oscillations to ν_τ (Ushida et al., ref. 4) and $\nu_\mu \rightarrow \nu_x$ (CDHS Collaboration, ref. 8 and Haber et al., ref. 4).
- Fig. 4: The ratio $r_{\text{obs}}/r_{\text{exp}}$ measured in the disappearance experiment is plotted versus the length ℓ (in number of subunits) of the events.

Fig. 1

Fig.2(a)

Fig.2(b)

Fig.3(a)

Fig.3(b)

Fig. 4