A SEARCH FOR DECAYS OF HEAVY NEUTRINOS

CHARM Collaboration

F. Bergsma, J. Dorenbosch, M. Jonker¹⁾ and C. Nieuwenhuis

NIKHEF, Amsterdam, The Netherlands

J.V. Allaby, U. Amaldi, G. Barbiellini²⁾, L. Barone³⁾, C. Berger⁴⁾, A. Capone³⁾,
W. Flegel, L. Lanceri, M. Metcalf, J. Panman and K. Winter

CERN, Geneva, Switzerland

I. Abt, J. Aspiazu, F.W. Büsler, H. Daumann, P.D. Gall, F. Niebergall,
F.H. Ranitzsch, P. Schütt and P. Stähelin

II. Institut für Experimentalphysik⁵⁾, Universität Hamburg, Hamburg, Fed. Rep. Germany

P. Gorbunov, E. Grigoriev, V. Kaftanov, V. Khovansky and A. Rosanov

Institute for Theoretical and Experimental Physics, Moscow, USSR

A. Baroncelli⁶⁾, B. Borgia⁷⁾, C. Bosio⁶⁾, M. Diemoz⁷⁾, U. Dore⁷⁾, F. Ferroni⁷⁾, E. Longo⁷⁾,
L. Luminari⁷⁾, P. Monacelli⁷⁾, F. de Notaristefani⁷⁾, P. Pistilli⁷⁾,
C. Santoni⁶⁾, L. Tortora⁶⁾ and V. Valente⁸⁾

Istituto Nazionale di Fisica Nucleare, Rome, Italy

ABSTRACT

A search for heavy neutrinos was conducted in the neutrino beam produced by the 400 GeV proton beam-dump and in the 400 GeV wide-band neutrino beam at CERN. A heavy neutrino associated with the τ lepton was searched for in the beam-dump experiment. No assumption on the nature of heavy neutrinos was made in the wide-band beam experiment. A search was made for neutrinos decaying into two electrons and a light neutrino. Since no events were observed, an upper limit on the neutrino mixing angles as a function of the neutrino mass is derived. The beam-dump experiment is sensitive to a neutrino mass range of 10–250 MeV and an upper limit at 90% confidence level on the square of the neutrino mixing angle of $\approx 10^{-10}$ was obtained for neutrino masses greater than 180 MeV. The wide-band neutrino experiment is sensitive to neutrinos with a mass in a larger range (10–490 MeV), and for masses greater than 250 MeV yields an upper limit on the square of the neutrino mixing angle of $\approx 10^{-6}$.

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¹⁾ Now at SLAC, Stanford, USA.

²⁾ On leave of absence from Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy.

³⁾ On leave of absence from Istituto di Fisica, University of Rome and INFN, Sezione di Roma, Italy.

⁴⁾ On leave of absence from Technische Hochschule, Aachen, Fed. Rep. Germany.

⁵⁾ Supported by Bundesministerium für Forschung und Technologie, Bonn, Fed. Rep. Germany.

⁶⁾ INFN Sezione Sanità and Istituto Superiore di Sanità, Rome, Italy.

⁷⁾ Istituto di Fisica, University of Rome and INFN, Sezione di Roma, Italy.

⁸⁾ Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy.

A search for heavy neutrinos with mass in the ranges 10–250 MeV and 10–490 MeV, performed using the 400 GeV proton beam-dump neutrino beam and the 400 GeV wide-band neutrino beam, respectively, is described in this letter.

In the conventional theory of weak interactions neutrinos are assumed to be massless, but experimentally a finite neutrino mass cannot be excluded [1–4]. The present limit on the τ neutrino mass is 250 MeV [4]. Assuming production of τ neutrinos by leptonic decays of the F-meson ($F \rightarrow \tau \nu_\tau$) and by the subsequent τ decay, the neutrino beam produced by high-energy protons interacting in a copper beam dump [5] would contain a large fraction of such heavy neutrinos.

Moreover if neutrinos are massive their weak (flavour) eigenstates are linear combinations of the mass eigenstates:

$$\nu_\ell = \sum U_{\ell i} \nu_i \quad (\ell = e, \mu, \tau, \dots; i = 1, 2, 3, \dots) \quad (1)$$

Neutrino beams can therefore contain a fraction of heavy neutrinos produced in π and K decay [6,7]. Neutrinos with mass larger than a few mega-electronvolts can decay into a light neutrino and two electrons. For neutrinos with mass larger than 110 MeV other decay channels are open ($\nu_1 \rightarrow e\mu\nu$, $\nu_1 \rightarrow e\pi$, ...) [6]. The decay probability for heavy neutrinos is proportional to the square of the mixing angles $|U_{\ell i}|$ defined in eq. (1). A search was made for neutrinos decaying into a pair of electrons [8]:

$$\nu_1 \rightarrow e^+ e^- \nu_e. \quad (2)$$

In the beam-dump experiment decays of heavy neutrinos were searched for in an empty decay region of 35 m length and $3 \times 3 \text{ m}^2$ cross-sectional area [9], parallel to the CDHS [10] and the CHARM [11] neutrino detectors. Another search for heavy neutrinos produced in π and K decays was performed in the horn-focused wide-band neutrino beam using the fine-grain CHARM calorimeter [12].

The layout of the beam-dump experiment [9] is shown in fig. 1. A veto scintillation counter plane of $6 \times 4.8 \text{ m}^2$ active area (SC1) defines the beginning of the decay volume. The decay region is parallel to the neutrino beam line at a mean distance of 5 m, corresponding to an angle with respect to the incident proton beam of 10 mrad. The detector is located at a distance of 480 m from the beam dump and covers a solid angle of $3.9 \times 10^{-5} \text{ sr}$. One module of the CHARM fine-grain calorimeter was displaced to the end of the decay region. This module has an active area of $3 \times 3 \text{ m}^2$. The performance of this module is well understood [12] and has been proved in many experiments. The energy of electromagnetic showers is measured in this module, which is 6 radiation lengths deep, with a resolution of $\Delta E/E < 0.30$ for shower energies $E > 5 \text{ GeV}$. The decay volume is subdivided into three regions using two sets of proportional tubes (P1 and P2) [12] (see fig. 1). Each set consists of four planes of proportional drift tubes, covering a surface of $4 \times 4 \text{ m}^2$, preceded by a lead converter of $1/2$ radiation length thickness. The first two planes of each set have wires which are aligned horizontally and the last two have them aligned vertically. The planes of a set are separated from one another by 15 cm. In order to improve the angular resolution of the shower and to better reconstruct the decay point, a low-density detector was added in front of the CHARM calorimeter module. This comprised three sets of proportional tubes (P3, P4, and P5) covering an area of $4 \times 4 \text{ m}^2$. In front of these sets a scintillation counter plane of the same area (SC2) was placed. The estimated angular resolution for an electromagnetic shower is a few milliradians.

The detector was exposed to a neutrino flux produced by 1.7×10^{18} protons on a solid copper target [5] and 0.7×10^{18} protons on a copper target laminated with an effective density of $1/3$ of that of solid copper [5]. In the combined exposures 21,000 events were collected satisfying the trigger requirements: no hits in the scintillator plane SC1 and a hit in at least 4 scintillator planes of the calorimeter module. These events include: cosmic-ray events (a track not pointing to the scintillator plane SC1), parasitic events (tracks from neutrino interactions in the CDHS and CHARM detectors or in the floor), beam-associated muons, and neutrino interactions. The events recognized as neutrino interactions having the shower vertex after the scintillator plane SC2 were used to check the performance of this decay detector. In this part of the decay detector 340 ± 45 neutrino interactions were observed. Based on the number of neutrino interactions observed in the CHARM calorimeter and taking into account the different mass and the different angle with respect to the proton beam [9], 440 ± 50 neutrino interactions were expected.

Events recognized to be cosmic rays entering the detector, parasitic events, and beam-associated muons were eliminated from the sample. The decay candidates were required to have at least one hit in the scintillator plane SC2 (corresponding to a decay region of 35 m length), and a shower energy larger than 3 GeV. The sample was scanned to look for candidates which are consistent with having two electrons. The scanning criteria were: in the case of a single hit in the scintillator plane SC2 the pulse height was required to be larger than that corresponding to the energy released by the passage of 1.5 minimum ionizing particles (9 MeV), and not more than 2 tracks in the proportional-tube sets P3, P4, and P5, or in the calorimeter module. No event satisfies these criteria.

Assuming that the ν_τ couples mainly to a single-mass eigenstate, an upper limit can be set on the square of the mixing angle $|U_{\ell i}|$ defined in eq. (1) (i is the dominant mass eigenstate of the τ neutrino). The expected number of neutrino decay events in the decay region was computed according to the expression:

$$N = N_F P[F \rightarrow \nu_\tau] A P[\nu_\tau \rightarrow e^+ e^- \nu_e]. \quad (3)$$

N_F is the number of F mesons produced by protons in the dump. It was computed from the number of prompt charged-current muon-neutrino events observed in the CHARM calorimeter [14]. During the exposure 1830 ± 250 prompt neutrino events with a muon in the final state having a shower energy larger than 2 GeV and a muon momentum larger than 1 GeV/c were collected. These events are produced essentially by muon-neutrinos coming from the semileptonic decay of D mesons ($BR = 0.1$). A ratio $\sigma(pCu \rightarrow F\bar{F}X)/\sigma(pCu \rightarrow D\bar{D}X) = 0.2$ was assumed. $P[F \rightarrow \nu_\tau]$ is the probability of the F meson to decay into a heavy neutrino. It is given by the product of the branching ratio for the F to decay into a zero mass neutrino ($BR = 0.03$) and a factor ρ depending on the neutrino mass. The factor A gives the fraction of heavy neutrinos, produced directly by F or by the subsequent τ decay, that cross the decay region. The production of F mesons was simulated by a Monte Carlo program assuming a distribution for the Feynman variable x corresponding to $(1-x)^4$ and a transverse momentum distribution proportional to $\exp(-2p_T)$. Cascade production was taken into account. The flux of τ neutrinos computed using this model agrees for zero neutrino mass with the limit obtained in an earlier beam-dump experiment [13] on the number of events induced by ν_τ : $N(\nu_\tau \text{ ev.})/N(\text{prompt ev.}) < 0.1$ at 90% confidence level. $P[\nu_\tau \rightarrow e^+ e^- \nu_e]$ is the probability for the heavy neutrinos to decay in the fiducial decay region, scaled from the decay matrix element of muon decay. It is proportional to the fifth power of the neutrino mass, to the average of the inverse of the neutrino energy, to the length of the decay region (35 m) and to the square of the mixing angle $|U_{e\tau}|^2$. The acceptance factor A and the average neutrino energy depend on the neutrino mass. The limit at 90% confidence level on the square of the mixing angle in the neutrino mass range 10–250 GeV is shown in fig. 2, together with previous results on $|U_{e\tau}|^2$ [15–17].

In the case of the wide-band neutrino-beam experiment no assumption was made on the nature of the heavy neutrino. The search for “two-electron events” was performed on a sample of 1.3×10^6 neutrino and 1.4×10^6 antineutrino interactions (produced by 1.4×10^{18} and 5.7×10^{18} protons on target, respectively) collected in the fine-grain CHARM calorimeter [12].

Candidate events were selected from those muonless events appearing as showers of narrow width, characteristic of showers initiated by electrons and photons in the CHARM calorimeter [12]. The selected events were required to have a shower energy E deposited in the calorimeter between 7.5 and 50 GeV and a value of the variable $E^2\theta^2$ below 0.54 GeV^2 (θ is the angle between the shower axis and the direction of the incoming neutrino). A total of 331 neutrino and 769 antineutrino events were selected.

The events surviving the selection criteria are due to the following known sources:

- a) elastic and quasi-elastic charged-current events induced by the electron-neutrino contamination of the beam;
- b) events induced by the scattering of neutrinos on electrons;
- c) neutral-current events with a γ or a π^0 in the final state produced by coherent scattering of muon-neutrinos on nuclei [18].

Showers initiated by the decay of massive neutrinos into two electrons or by a γ or π^0 from reaction (c) deposit in the first scintillator plane following the shower vertex an energy (E_f) larger than that released by one minimum ionizing particle (6 MeV), whilst a substantial fraction of the showers due to single electrons induced by reactions (a) and (b) give an energy deposition corresponding to one minimum ionizing particle [19]. The total number of events due to reactions (a) and (b) was obtained from the subsample of the events with $E_f < 8 \text{ MeV}$ by a study of the event distribution versus the variable $E^2\theta^2$. A fraction corresponding to 0.33 ± 0.01 of the events induced by reaction (a) have $E^2\theta^2 < 0.12 \text{ GeV}^2$, while this fraction is equal to 0.90 ± 0.02 for the events induced by reaction (b) [19]. The fraction of the events with $E_f < 8 \text{ MeV}$ has been measured to be 0.32 ± 0.05 in the case of the scattering of neutrinos on electrons and 0.26 ± 0.06 for the elastic and quasi-elastic scattering of electron-neutrinos on nucleons [19]. The number of events induced by the process (c) and possibly by the decay of massive neutrinos into two electrons were computed from the events with $E_f > 8 \text{ MeV}$ after the subtraction of the events attributed to reactions (a) and (b). The separation between events from reaction (c) and neutrino decay candidates is done using again the event distribution versus the variable $E^2\theta^2$. The fraction of the events induced by reaction (c) having $E^2\theta^2 < 0.12 \text{ GeV}^2$ is 0.28 ± 0.02 [19]. For the showers produced by massive neutrino decays this fraction varies between 0.9 and 0.6, depending on the nature of the charged lepton (e, μ) produced together with the neutrino in π or K decay and on the neutrino mass.

The results of this analysis for neutrino masses below 140 MeV are summarized in table 1; only statistical errors are given. The number of events attributed to heavy neutrino decay is compatible with zero (1 ± 41 events in the case of a muon partner and 1 ± 49 events in the case of an electron partner). If this experiment were performed with the decay detector, the efficiency for observing heavy neutrino decays could be improved by one or two orders of magnitude.

From this result, taking into account the statistical errors and the uncertainties on the background subtraction, a limit on the product of the mixing angles as defined in eq. (1) can be obtained. The expected number of neutrino decay events in the CHARM calorimeter is computed according to the equation:

$$N = \{N_\pi P[\pi \rightarrow \nu_i] A_\pi + N_K P[K \rightarrow \nu_i] A_K\} P[\nu_i \rightarrow e^+ e^- \nu_e] \varepsilon, \quad (4)$$

where N_π and N_K are the numbers of π and K decays which were the origin of the neutrino flux, corresponding to the neutrino and antineutrino interactions collected in the CHARM detector. They were computed using the wide-band

beam Monte Carlo simulation program [20]. $P[\pi(K) \rightarrow \nu_i]$ is the probability of $\pi(K)$ decaying into a heavy neutrino. It is proportional to $|U_{ei}|^2$ or to $|U_{\mu i}|^2$, depending on whether the heavy neutrino is produced with an electron or a muon, and is obtained from the probability of π or K decaying into a zero-mass neutrino times a factor ρ depending on neutrino mass. In the case of two-body decays ρ takes into account that for finite neutrino mass there is less suppression due to helicity conservation than in the case of a zero-mass neutrino [5]. The geometrical factors A_π and A_K give the fraction of the heavy neutrinos from π and K decay crossing the CHARM detector. $P[\nu_i \rightarrow e^+e^- \nu_e]$ is the probability of the heavy neutrinos decaying in the fiducial volume of the detector. The decay length is 12 m. The global efficiency of the cuts applied in the analysis (ϵ) includes the efficiency of selecting electromagnetic showers induced by two electrons (0.44 ± 0.04) and the efficiency of the shower energy cuts: 7.5–50 GeV. The acceptance factors A_π and A_K , the neutrino energy, and the efficiency of the selected shower energy range depend on the neutrino mass.

The limits derived at 90% confidence level on $|U_{ei}|^2$, in the neutrino mass range 10–490 MeV, and on $|U_{ei} U_{\mu i}|^2$, in the neutrino mass range 10–380 MeV, are shown in figs. 2 and 3, respectively. The uncertainties in the selection of electromagnetic showers and in the normalization factors N_π and N_K (7%) are included. The limits on $|U_{ei} U_{\mu i}|$ cannot be directly compared with published limits because they refer only to $|U_{ei}|^2$ and $|U_{\mu i}|^2$ [15–17, 21–23]. It should be noted that for larger mixing angles (> 0.1) the wide-band neutrino experiment reported here is not sensitive to neutrino masses larger than 350 MeV, since the beam would be strongly attenuated by decays before reaching the CHARM detector, which is ≈ 900 m from the neutrino source.

In conclusion, there is no evidence for the decay of heavy neutrinos into two electrons with mass in the range 10–490 MeV. In the beam-dump experiment an upper limit at 90% confidence level on the square of the neutrino mixing angles of 10^{-10} was obtained for a τ neutrino mass greater than 180 MeV. The wide-band beam experiment is sensitive to values of the square of the neutrino mixing angle of $\sim 10^{-6}$ for neutrino masses greater than 250 MeV.

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Table 1

Wide-band neutrino-beam experiment: results of the analysis for neutrino masses below 140 MeV*

	$E_f < 8 \text{ MeV}$	$E_f > 8 \text{ MeV}$
Elastic and quasi-elastic ν_e events	127 ± 36	369 ± 40
$\nu_\mu e$ scattering events	41 ± 11	87 ± 24
Coherent π^0/γ events	3 ± 0.3	472 ± 50
Neutrino decay events (partner: μ)	0 ± 0.3	1 ± 41
Neutrino decay events (partner: e)	0 ± 0.3	1 ± 49

* For larger neutrino masses, acceptance effects change the sensitivity by a factor of $\sim 1/2$.

Figure captions

- Fig. 1 Layout of the decay beam-dump experiment. SC1 and SC2 are scintillator planes. SC1 is used as a veto counter. P1 to P5 are sets of 4 planes of proportional drift tubes. The calorimeter module is 6 radiation lengths deep.
- Fig. 2 Limits at 90% confidence level on $|U_{ei}|^2$ (the square of the coupling strength of mass eigenstate i to the electron-neutrino weak eigenstate) as a function of the neutrino mass: a) limits obtained in the proton beam-dump (BD) experiment (the mass eigenstate is identified with the τ neutrino); b) limits obtained in the wide-band neutrino beam (WBB) experiment (this experiment is not sensitive to values of $|U_{ei}|^2 > 0.1$ for neutrino masses larger than 350 MeV); c) limits from solar neutrino measurements [15]; d) limits from the measurement of the branching ratio $\pi \rightarrow \nu e$ [16]; e) limits obtained from the search for monoenergetic peaks in the region below the value predicted for the zero-mass neutrino in $\pi \rightarrow \nu e$ decay [16]; f) limits from the measurement of the branching ratio $K \rightarrow \nu e$ [17].
- Fig. 3 Limits at 90% confidence level on $|U_{ei}U_{\mu i}|$ as a function of the neutrino mass obtained in the WBB experiment; $|U_{ei}|$ and $|U_{\mu i}|$ are the coupling strengths of a mass eigenstate i to the electron and muon neutrino weak eigenstate, respectively.

Fig. 1

Fig. 2

Fig. 3