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A SEARCH FOR DECAYS OF HEAVY NEUTRINOS IN THE MASS RANGE 0.5-2.8 GeV

The CHARM Collaboration

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Abstract

A search for decays of heavy neutrinos was conducted by the CHARM Collaboration in a prompt neutrino beam produced by dumping 400 GeV protons in a Cu target, and in the CERN wide-band neutrino beam produced by 400 GeV primary protons. No candidate event was found. In the beam-dump experiment heavy neutrinos have been assumed to be produced by mixing in charmed D meson decays. Neutrinos decaying into $e^+e^-\nu_e$, $\mu^+e^-\nu_e$, $e^+\mu^-\nu_\mu$, and $\mu^+\mu^-\nu_\mu$ were searched for. Limits of $|U_{ei}|^2, |U_{\mu i}|^2 < 10^{-7}$ were obtained for neutrino masses around 1.5 GeV. In the wide-band experiment heavy neutrinos were assumed to be produced by neutral-current neutrino interactions in the CHARM calorimeter. Here a search was made for neutrinos decaying into a μ and hadrons. This experiment is sensitive to decays of neutrinos with mass in the range 0.5-2.8 GeV with limits of $|U_{\mu i}|^2 < 3 \times 10^{-4}$ for masses around 2.5 GeV. These measurements extend our previous results in the mass range 10-400 MeV.

Neutrinos may have Dirac or Majorana masses. If such mass eigenstates ($\nu_1, \nu_2, \nu_3, \dots$) do exist, they need not coincide with the weak (flavour) ($\nu_e, \nu_\mu, \nu_\tau, \dots$) eigenstates, but rather with a linear combination of them

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

where $U_{\ell i}$ are the elements of a mixing matrix. The charged-current coupling of the massive neutrino ν_i to the charged lepton ℓ is proportional to the square of $U_{\ell i}$. There are models [1] in which the neutral-current interactions of the heavy neutrinos change their flavour. In this case there may be other contributions to the mixing than $U_{\ell i}$; however this possibility was neglected in the present analysis. The mixing matrix (1) could induce neutrino oscillations [2] and neutrino decays [3], depending on the mass differences of neutrinos.

In this letter results from a search for decays of heavy neutrinos with masses in the range 0.5-1.8 GeV and 0.5-2.8 GeV are reported. The search was done by the CHARM Collaboration using the prompt neutrino beam produced by dumping 400 GeV protons on a thick copper beam dump (BD), and the wide-band neutrino beam (WBB) produced by 400 GeV primary protons. Results on a search for decays of neutrinos in the mass range 10-400 MeV were previously reported [4]. Preliminary results extending this search to mass values up to 2 GeV have already been presented in 1983 [5].

In the BD experiment heavy neutrinos have been assumed to be produced in the decays of charmed D mesons. The neutrino decays [3]:

$$\nu_i \rightarrow e^+ e^- \nu_e, \quad (2a)$$

$$\nu_i \rightarrow \mu^+ \mu^- \nu_\mu, \quad (2b)$$

$$\nu_i \rightarrow e^+ \mu^- \nu_e, \mu^+ e^- \nu_\mu. \quad (2c)$$

and the corresponding channels of antineutrinos, were searched for in an empty decay region of 35 m length and $3 \times 3 \text{ m}^2$ cross-section area [4], parallel to the CDHS [6] and to the CHARM [7] neutrino detectors (see fig. 1).

In the WBB experiment, heavy neutrinos were assumed to be produced in the CHARM calorimeter [7] by muon neutrinos via a neutral-current interaction:

$$\nu_{\mu} N \rightarrow \nu_1 X . \quad (3)$$

The subsequent decays into a muon and hadrons [3]:

$$\nu_1 \rightarrow \mu X . \quad (4)$$

were searched for in the calorimeter itself.

The decay detector, shown in fig.1, has already been described elsewhere [4]. The decay region, defined by the scintillator planes SC1 and SC2, was 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 covered a solid angle of 3.9×10^{-5} sr. One module of the CHARM fine-grain calorimeter [7] was displaced to the end of the decay region. The decay volume was subdivided into three regions using two sets of four proportional tube planes (P1 and P2) [8] (see fig. 1). In order to improve the angular resolution of the shower and to reconstruct better the decay point, three sets of four proportional tube planes (P3, P4, and P5) were installed in front of the CHARM calorimeter module.

The signature of reactions (2) would be events originating in the decay region at a small angle with respect to the neutrino beam axis with one or two separate electromagnetic showers [decay (2a)], two tracks [decay (2b)], and one electromagnetic shower and one track in the case of the decay (2c).

The detector was exposed to a neutrino flux produced by 1.7×10^{18} protons on a solid copper target and 0.7×10^{18} protons on a laminated copper target with an effective density of 1/3 of that of solid copper [4]. In the combined exposures, 21,000 events were collected satisfying the trigger requirements of no hit in the scintillator plane SC1 and a hit in at least 4 out of the 6 scintillator planes of the calorimeter module.

Candidates due to heavy neutrino decays have been selected from a sample of events which is dominated by inelastic scattering of electron- and muon-neutrinos and antineutrinos producing hadron showers. Compared with heavy neutrino decay events with an electron or an electron pair, such events have a broader reconstructed angular distribution because of intrinsic resolution and leakage effects.

The regularity of the development of electromagnetic showers was used to distinguish further between these two types of events. In particular, the distributions of the deviation of the reconstructed shower axis from the incoming beam direction and the fraction of the energy detected by the proportional drift tubes of the calorimeter module outside a narrow cone around the shower axis for the decay events have been evaluated by a Monte Carlo method [9]. No event compatible with the features of reaction (2a) was found. The muons produced in the neutrino decay were identified by track reconstruction; again no event candidate for the reactions (2b) and (2c) was found.

The expected number of decays in the decay region of heavy neutrinos with mass m was computed from the expression:

$$N = N_D P[D \rightarrow \nu_i(m)] A(m) P[\nu_i(m) \rightarrow \ell'^+ \ell^- \nu_\ell] \varepsilon(m), \quad (5)$$

where N_D , the number of D mesons produced by protons in the dump, was calculated from the number of prompt single-muon events observed in the CHARM calorimeter (1830 ± 250) [4], during the same exposure. Heavy neutrinos can be produced in the semileptonic decay of charged and neutral D's and in the leptonic decay of charged D's. A ratio $\sigma(D^\pm) = \sigma(D^0)/2$ was assumed. The probability $P[D \rightarrow \nu_i(m)]$ of the D meson to decay into a neutrino i of mass m and a lepton ℓ ($\ell = e, \mu$) is proportional to $|U_{\ell i}|^2$.

The acceptance factor $A(m)$ gives the fraction of heavy neutrinos that cross the decay region. In the acceptance calculation the production of D mesons was simulated by a Monte Carlo program, assuming a distribution for the Feynman variable x corresponding to $(1-x)^5$ and a transverse momentum distribution proportional to $\exp(-2p_t)$ [p_t in GeV]. This parametrization described satisfactorily the energy spectrum of prompt $\nu_\mu, \bar{\nu}_\mu$ observed in the calorimeter. The production of D mesons in the dump was computed taking into account hadron cascade as well as primary proton interactions.

The probability $P[\nu_i(m) \rightarrow \ell'^+ \ell^- \nu_\ell]$ ($\ell, \ell' = e, \mu$) for the heavy neutrino to decay in the fiducial decay region according to reaction (2) is proportional to $|U_{\ell i}|^2$. The factor $\varepsilon(m)$ describes the efficiency of the estimators to select events induced by reactions (2). For a neutrino mass of 1 GeV the values of $\varepsilon(m)$ for the three decay modes are $\approx 60\%$ ($\nu_i \rightarrow e^+ e^- \nu$), $\approx 75\%$ ($\nu_i \rightarrow \mu^+ \mu^- \nu$), and $\approx 65\%$ ($\nu_i \rightarrow e \mu \nu$).

The 90% confidence limits on the square of the mixing angles $|U_{ei}|^2$ and $|U_{\mu i}|^2$ as a function of the neutrino mass are shown in fig. 2 and fig. 3 (curve a) together with previous results [4, 10-18]. For large mixing angles the sensitivity of this experiment is limited to small masses (i.e. for $|U_{\ell i}|^2 > 10^{-1}$ it is sensitive to $m_{\nu_i} < 1000$ MeV and for $|U_{\ell i}|^2 > 10^{-4}$ to $m_{\nu_i} < 1500$ MeV) because the beam of heavy neutrinos is attenuated by decay before reaching the detector, which is located at a distance of 480 m from the target. The limits (d) in fig. 2 have been obtained by the CHARM Collaboration, assuming that the neutrino associated with the τ lepton is massive [4]. Such neutrinos are produced in the chain $F \rightarrow \tau \nu_3$, $\tau \rightarrow \nu_3 X$. The limits have been computed using for the F and τ masses the values $m_F = 1.971$ GeV and $m_\tau = 1.784$ GeV. They have been limited to the region $m_{\nu_i} < 70$ MeV because of the recent limit on the mass of ν_τ obtained by the Argus Collaboration studying the decay $\tau \rightarrow 3\pi \nu_\tau$ [19]. The limits (i) in fig. 2 and (g) in fig. 3, quoted in ref. 15, have been obtained under the hypothesis that the heavy neutrinos belong to a weak doublet.

To obtain limits for decays of heavy neutrinos with larger masses the search was extended to a sample of 1.04×10^5 neutrino and 2.64×10^5 antineutrino interactions collected in the fine-grain CHARM calorimeter [5] exposed to the CERN WBB. The topology of events induced by the production of heavy neutrinos according to reaction (3) and their subsequent decay in the calorimeter by reaction (4) would show two showers separated by a gap along the beam direction, and with a muon pointing to the vertex of the second one. Since in this experiment neutrinos decaying over an average distance of 6 m from the production point were searched for, the sensitivity is restricted to the mass range 0.5-2.8 GeV and to mixing angles larger than 10^{-4} . The following criteria were applied to select such events: (i) the interaction point was required to be in a fiducial region of square-cross section 240×240 cm² in the transverse direction; the vertex of the first shower was required to occur between planes 5 and 55 out of the 78 calorimeter planes and the event had to be fully contained in the target calorimeter; (ii) the visible total energy was required to be larger than 0.5 GeV; (iii) the largest fraction of event candidates was due to random superpositions of two different events occurring in the gate time of the trigger; events were selected which had the same event pattern of the proportional drift tubes and of the scintillators [20].

About 20,000 events showing two showers were retained and 41 of them are separated longitudinally by at least one quiet scintillator plane. This sample of events still contains a small fraction of random superpositions of uncorrelated events occurring in the scintillator gate time. Their number can be obtained by scaling the number of events rejected by selection criterion (iii) by using the fact that the gate time of the scintillators is ten times smaller than that of the tube system.

The following topologies were searched for in this sample of events: 1) events without any μ -track candidate, either from the primary shower, or from the secondary one; 2) events with a μ -track emerging from both showers; 3) events with a μ -track emerging either from a) the primary vertex or b) the secondary vertex. The results of this search are reported in table 1. Categories (1) and (3a) contain 38 events of which 3.6 ± 0.7 are estimated to be random superposition events. The number of events left is fully compatible with the expected number of secondary showers induced by K^0_L and neutrons produced by the first shower, as shown by a ν ($\bar{\nu}$) induced shower simulation [21]. These events were found to be $\approx 10^{-4}$ of the total ν and $\bar{\nu}$ interactions, corresponding to about 30 events. The number of events found in categories (2) and (3b) is 3, while the expected number of background events is 3.3 ± 0.6 . In particular, only one event of category (3b), which are candidates of the chain of reactions (3) and (4), was found to contain a muon emerging from the secondary shower. The estimated number of background events of this category is 1.9 ± 0.4 .

The expected number N of decays of heavy neutrinos with mass m in the fiducial volume of the calorimeter was computed according to the expression

$$N = N_{\nu_1(m)} P[\nu_1(m) \rightarrow \mu X] \epsilon(m), \quad (6)$$

where $N_{\nu_1(m)}$ is the number of heavy neutrinos produced in a neutral-current neutrino interaction. It was obtained from the number of neutral-current events collected in the calorimeter during the exposure times the square of the mixing angle $|U_{\mu 1}|^2$, taking into account the threshold effect due to the heavy neutrino mass. The probability $P[\nu_1(m) \rightarrow \mu X]$ for the heavy neutrino to decay in the fiducial volume is proportional to $|U_{\mu 1}|^2$.

The efficiency of selecting heavy neutrino decay events $\epsilon(m)$ was computed in a way very similar to the one used in a previous search for fractionally charged particles [20]. Two real single-shower

events with hadron energy larger than 2 GeV were selected at random from a sample of neutrino and antineutrino induced WBB events. These events were superimposed by placing the second one at a pre-determined position with respect to the first one; these pseudo-events were then processed by the analysis program to identify events with two showers. The efficiency of this automatic selection was computed for different combinations of hadronic energies and different relative distances between the two showers. For showers with energy between 5 and 25 GeV at a distance larger than 3 m the efficiency of the algorithm is $\approx 95\%$. These efficiency values were then used in a simulation program which calculated the overall acceptance of the detector for different combinations of neutrino masses and values of the square of the mixing angle $|U_{\mu 1}|^2$. Heavy neutrino production in (anti)neutrino neutral-current interactions was described by assuming that the hadron energy distribution is equal to the one measured in neutral-current events [22]. Having observed one heavy neutrino candidate event, and expecting 1.9 ± 0.4 background events, the 90% confidence limit on $|U_{\mu 1}|^2$ was computed by inserting $N = 2$ into eq. (6). The results are shown in fig. 3 (curve b).

In conclusion, there is no evidence for decay of heavy neutrinos with mass in the range up to 2.8 GeV. In this search the limits on inter-family mixing of neutrinos have been extended to $|U_{e 1}|^2$, $|U_{\mu 1}|^2 < 10^{-7}$ for $m_{\nu_1} \approx 1.5$ GeV and to $|U_{\mu 1}|^2 < 3 \times 10^{-4}$ for $m_{\nu_1} \approx 2.5$ GeV.

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Table 1

Classification of selected two-shower events in the WBB
experiment according to their topologies.

Class	Topology	Number of events	Background due to K_L^0 and n	Background due to random superposition
1		14	10 ± 4	2.0 ± 0.5
2		2	-	1.4 ± 0.4
3a		24	20 ± 6	1.6 ± 0.4
3b		1	-	1.9 ± 0.4

Figure Captions

- Fig. 1 Layout of the decay detector with a decay region of 35 m length and 9 m² surface area. SC1 is a veto scintillator plane and SC2 is a scintillator hodoscope. P1 to P5 are arrays of 4 planes of proportional drift tubes. The calorimeter module is 6 radiation lengths long. Lead converters of 0.5X⁰ each were placed in front of P1, P2, P4 and P5.
- Fig. 2 Limits at 90% confidence level on $|U_{ei}|^2$ (the square of the coupling strength of the mass eigenstate i to the electron-neutrino weak eigenstate) as a function of the neutrino mass: a) limits obtained in this experiment by the CHARM Collaboration; b) limits from solar neutrinos [10]; c) limits obtained studying the decay $\pi \rightarrow \nu e$ [11]; d) limits obtained by the CHARM Collaboration in a beam dump experiment [4] assuming that heavy neutrinos are produced in the chain $F \rightarrow \tau \nu_3$, $\tau \rightarrow \nu_3 X$; e) limits from the measurement of the branching ratio $K \rightarrow \nu e$ [12]; f) limits obtained in a previous wide-band neutrino beam experiment by the CHARM Collaboration [4]; g) limits from the study of the decay $K \rightarrow \nu e$ at KEK [13]; h) limits obtained in the beam-dump experiment by the BEBC Collaboration [14]; i) limits obtained from a search for secondary vertices in the MARK II experiment assuming that the heavy neutrinos are produced by the reaction $e^+e^- \rightarrow \nu_1 \bar{\nu}_1$ [15]; j) limits obtained in a search for monojet events due to the reaction $e^+e^- \rightarrow \nu_e \bar{\nu}_1$ [16].
- Fig. 3 Limits at 90% confidence level on $|U_{\mu i}|^2$ (the square of the coupling strength of the mass eigenstate i to the muon-neutrino weak eigenstate) as a function of the neutrino mass: a) limits obtained in this experiment (beam dump) by the CHARM Collaboration; b) limits obtained in this experiment (wide-band neutrino beam) by the CHARM Collaboration; c) limits obtained studying the decay $\pi \rightarrow \nu \mu$ at SIN [17]; d) limits from the study of the decay $K \rightarrow \nu \mu$ at KEK [13]; e) limits from the study of the decay $K \rightarrow \nu \bar{\nu} \nu \mu$ at LBL [18]; f) limits obtained by the BEBC Collaboration in the beam-dump experiment [14]; g) limits obtained from a search for secondary vertices in the MARK II experiment assuming that the heavy neutrinos are produced by the reaction $e^+e^- \rightarrow \nu_1 \bar{\nu}_1$ [15].

Fig. 1

Fig. 2