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LIMITS ON THE MIXING OF TAU NEUTRINO TO HEAVY NEUTRINOS

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Abstract

Limits at 90% c.l. on the square of the mixing strength $|U_{\tau 4}|^2$ between ν_τ and a mostly isosinglet heavy neutrino with mass in the range 10–290 MeV/c^2 are reported. The results were derived using the negative result of a search for neutral particles decaying into two electrons conducted by the CHARM collaboration in a neutrino beam dump experiment. Upper limits $\cong 10^{-4}$ were obtained for neutrino masses larger than 160 MeV/c^2.

Keywords : Neutrino mixing, Neutrino decay

Neutrinos may have Dirac or Majorana masses. In general the mass eigenstates $(\nu_1, \nu_2, \nu_3, \nu_4, \ldots)$ do not coincide with the weak (flavour) $(\nu_e, \nu_\mu, \nu_\tau, \nu_s, \ldots)$ eigenstates, but rather with a linear combination of them

$$\nu_l = \sum_i U_{li} \nu_i \quad (l = e,\, \mu,\, \tau,\, s,\, \ldots;\, i = 1, 2, 3, 4,\, \ldots) \quad . \tag{1}$$

Such a mixing could result in neutrino oscillations when the mass differences are small, and in neutrino decays when the mass differences are large.

In this paper we report limits on the square of the mixing strength $|U_{\tau 4}|^2$ between ν_τ and a heavy neutrino, ν_4, mostly isosinglet under the Standard $SU(2)_L$ gauge group, with mass in the range 10–290 MeV$/c^2$. The limits were obtained using the negative result of a search for events produced by the decay of neutral particles into two electrons performed by the CHARM Collaboration in a neutrino beam dump experiment [1]-[4]. The decays of the neutral particles, produced in the dumping of 400 GeV protons in a Cu target, were looked for in a volume located at a distance of $L = 480$ m from the beam dump.

The decay detector, shown in Fig.1, has already been described elsewhere [5]. It had an empty decay region of $D = 35$ m length and 3 m $\times$ 3 m surface area defined by a veto scintillator plane (SC1) and a scintillator hodoscope (SC2). The volume was subdivided into three regions using two sets of four proportional tube planes (P1 and P2) [6]. One module of the CHARM fine-grain calorimeter [6] was displaced to the end of the decay region. In order to improve the resolution of the shower angle measurement and to reconstruct better the decay point, three sets of four proportional tube planes (P3, P4 and P5) were installed in front of the module. Lead converters of $0.5 X_0$ each were placed in front of P1, P2, P4 and P5. The detector 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, and covered a solid angle of 3.9×10^{-5} sr. The signature of the neutral particles decaying into two electrons 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.

The detector was exposed to a neutrino flux produced by 1.7×10^{18} protons on a solid copper target [7] and 0.7×10^{18} protons on a copper target laminated with an effective density of one-third of that of solid copper [7]. In the combined exposures, 21 000 events were collected satisfying the trigger requirements of no hit in the scintillator planes SC1 and a hit in at least four out of the six scintillator planes of the calorimeter module. The events were further selected requiring that the transverse co-ordinates of the shower vertex lie in a square of 2.5 m $\times$ 2.5 m centered on the detector axis and that the electron energy, $E_{\rm el}$, measured in the calorimeter module, be larger than 2 GeV. The events recognised as cosmic rays were also rejected. The remaining sample of 7185 events is dominated by inelastic scattering of electron- and muon-neutrinos and antineutrinos producing hadron showers. Compared with the decay of neutral particles into two electrons, such events have a broader reconstructed angular distribution because of the intrinsic resolution and leakage effects. The regularity of the development of electromagnetic showers was used to distinguish further between the signal and the background events. In particular, the distribution of the deviation of the reconstructed direction of the (two) shower(s) from that of the incoming beam and the fraction of the energy detected by the proportional drift tubes of the calorimeter module outside a narrow cone

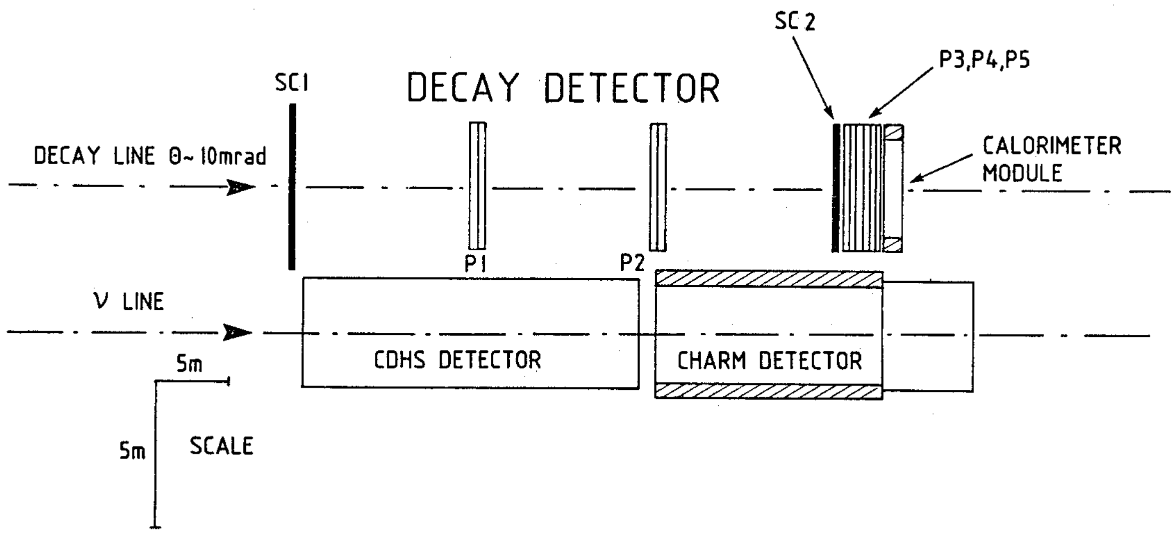
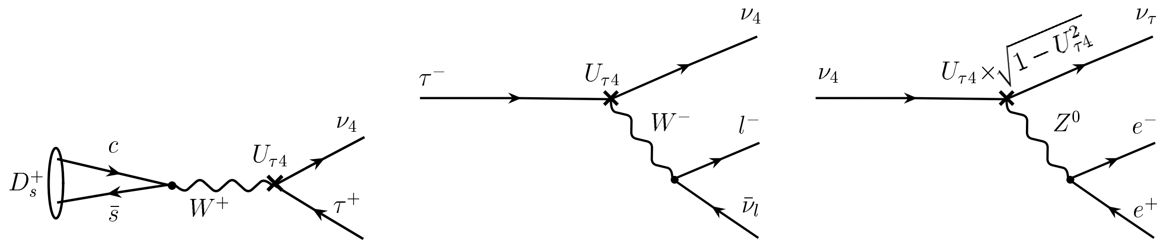


Figure 1: Layout of the decay detector.

around the shower were evaluated for the decay events by a Monte Carlo method [4]. No event compatible with the features of the decay of a neutral particle into two electrons was found.



a) b) c)

Figure 2: Feynman diagrams illustrating: (a) ν_4 production from D_s^+; (b) leptonic decay of τ^- into a heavy neutrino; (c) decay of an isosinglet neutrino ν_4 according to mode (4).

In this analysis we assumed that the ν_4 couples to matter essentially via mixing with ν_τ ($|U_{e4}|^2$, $|U_{\mu 4}|^2 << |U_{\tau 4}|^2$) and we studied the proton production of D_s's in the target and their decay into τ. The heavy neutrino is produced in the charged current decays

$$D_s \rightarrow \nu_4 + \tau \tag{2}$$

and

$$\tau \rightarrow \nu_4 + ... \quad . \tag{3}$$

The Feynman diagrams of the process (2) and of the decay $\tau^- \rightarrow \nu_4 + l^- + \bar{\nu}_l$ ($l = e, \mu$) are shown in Fig.s 2a and 2b respectively. On the basis of the assumptions made, the isosinglet heavy neutrino decays only via neutral current interactions according to the modes

$$\nu_4 \to \nu_\tau + \mathrm{e}^+ + \mathrm{e}^- \tag{4}$$

$$\nu_4 \to \nu_\tau + \nu_l + \bar{\nu}_l \quad (l = \mathrm{e},\, \mu \,\mathrm{and}\, \tau) \tag{5}$$

$$\nu_4 \to \nu_\tau + \mu^+ + \mu^- \tag{6}$$

$$\nu_4 \to \nu_\tau + \pi^0 \quad . \tag{7}$$

The Feynman diagram illustrating the signal decay channel (4) is shown in Fig. 2c. The channels (5)–(7) contribute to the beam attenuation. The branching ratio of mode (6) is negligible and the decay (7) opens for neutrino masses larger than the π^0 mass. The total decay width is then given by

$$\begin{aligned}\Gamma_{\mathrm{tot}} = \; & \Gamma\left(\nu_4 \to \nu_\tau + \nu_l + \bar{\nu}_l\right) + \Gamma\left(\nu_4 \to \nu_\tau + e^+ + e^-\right) + \\ & +\theta\left(m_{\nu_4} - m_{\pi^0}\right) \Gamma\left(\nu_4 \to \nu_\tau + \pi^0\right) \; .\end{aligned} \tag{8}$$

For heavy neutrinos with mass larger than 290 MeV/c^2 other decay modes open. The leptonic partial width is predicted to be [8]:

$$\begin{aligned}& \Gamma\left(\nu_4 \to \nu_\tau + \nu_l + \bar{\nu}_l\right) + \Gamma\left(\nu_4 \to \nu_\tau + e^+ + e^-\right) = \\ & = K \left[\frac{\left(1 + \tilde{g}_{\mathrm{L}}^2 + g_{\mathrm{R}}^2\right) G_{\mathrm{F}}^2 m_{\nu_4}^5 \left|U_{\tau 4}\right|^2 \left(1 - \left|U_{\tau 4}\right|^2\right)}{192\pi^3} \right] \; ,\end{aligned} \tag{9}$$

where $\tilde{g}_{\mathrm{L}} = g_{\mathrm{L}} - 1 = -1/2 + \sin^2\theta_{\mathrm{W}}$ and $g_{\mathrm{R}} = \sin^2\theta_{\mathrm{W}}$, θ_{W} is the weak angle. In this study the neutrinos were assumed to have Dirac masses and then $K = 1$. For Majorana neutrinos K is equal to 2. The leptonic partial width is dominated by the mode (5):

$$\frac{\Gamma\left(\nu_4 \to \nu_\tau + \mathrm{e}^+ + \mathrm{e}^-\right)}{\Gamma\left(\nu_4 \to \nu_\tau + \nu_l + \bar{\nu}_l\right) + \Gamma\left(\nu_4 \to \nu_\tau + \mathrm{e}^+ + \mathrm{e}^-\right)} \cong 0.14 \quad . \tag{10}$$

The partial width for the decay (7) is predicted to be [9]

$$\Gamma\left(\nu_4 \to \nu_\tau + \pi^0\right) = K \left[\frac{G_{\mathrm{F}}^2 m_{\nu_4} \left(m_{\nu_4}^2 - m_{\pi^0}^2\right) f_\pi^2 \left|U_{\tau 4}\right|^2 \left(1 - \left|U_{\tau 4}\right|^2\right)}{16\pi} \right] \quad . \tag{11}$$

We neglected possible contributions to the signal from the decay $\nu_4 \to \nu_\tau + \gamma$ [10]. This will make our result slightly more conservative.

For a given heavy neutrino mass m_{ν_4} the number of the decay events (4) expected in the detector is

$$N = \varepsilon\left(m_{\nu_4}\right) \int \Phi\left(E_{\nu_4}\right) P_{\nu_4 \to \nu_\tau e^+ e^-}\left(E_{\nu_4}\right) \, dE_{\nu_4} \quad , \tag{12}$$

where $\Phi\left(E_{\nu_4}\right)$ is the differential flux of heavy neutrinos, $P_{\nu_4 \to \nu_\tau e^+ e^-}\left(E_{\nu_4}\right)$ is the probability for a heavy neutrino of energy E_{ν_4} to decay in the decay fiducial volume according to reaction (4), and $\varepsilon\left(m_{\nu_4}\right)$ is the efficiency of the selection criteria of one or two electrons in the calorimeter based on the regularity of the development of electromagnetic showers and the collinearity between the (two) shower(s) and neutrino direction. The flux $\Phi\left(E_{\nu_4}\right)$ is given by

$$\Phi\left(E_{\nu_4}\right) = N_{\mathrm{p}} \frac{\sigma_{D_s}}{\sigma_{\mathrm{inel}}} \left[\begin{array}{l} \mathrm{BR}\left(D_s \to \nu_4 + \tau\right) A_{\nu_4}^{D_s} \phi_{\nu_4}^{D_s}\left(E_{\nu_4}\right) + \\ +\mathrm{BR}\left(D_s \to \nu_\tau + \tau\right) \mathrm{BR}\left(\tau \to \nu_4 + ...\right) A_{\nu_4}^{\tau} \phi_{\nu_4}^{\tau}\left(E_{\nu_4}\right) \end{array} \right] \quad . \tag{13}$$

The number of protons on the target corrected for the detector dead time, 13.6% for the solid target and 21.7% for the laminated one, is $N_{\rm p} = 2.0\times10^{18}$. The fraction of proton inelastic interactions leading to a charged D_s is given by [11]

$$\frac{\sigma_{D_s}}{\sigma_{\rm inel}} = \frac{A_{\rm Cu}\,[\sigma\,(D_s)/\sigma\,(D)]\,\sigma_D^{\rm nucleon}}{\sigma_{\rm inel}^{\rm Cu}} = 2.98\times10^{-4} \quad , \tag{14}$$

where the copper mass number is $A_{\rm Cu} = 63.55$. Linear A dependence is assumed for charm production. The used values of the inelastic proton cross–section, $\sigma_{\rm inel}^{\rm Cu}$ [12], of the ratio of the production cross–section for $D_s^\pm$ over the production cross–section for $D^\pm + D^0$, $\sigma\,(D_s)/\sigma\,(D)$ [13], and of the inclusive cross–sections for the production of D mesons, $\sigma_D^{\rm nucleon}$ [14], are reported in Table 1. The ratio $\sigma\,(D_s)/\sigma\,(D)$ was obtained by the Beatrice experiment studying charmed particles produced by π^-'s of 350 GeV/c [13]. It is compatible with the results obtained by $\rm e^+e^-$ experiments at center of mass energies equal to 10 GeV and at $\rm Z^0$ mass [15]. The value of $\sigma_D^{\rm nucleon}$ was obtained by the NA27 Collaboration studying the production of D's in the interactions of 400 GeV protons in an $\rm H_2$ target [14].

Parameters	Values	Systematicerrors [%]
$\sigma_{\rm inel}^{\rm Cu}$ [mb] [12]	769 ± 23	3.0
$\sigma\,(D_s)/\sigma\,(D)$ [13]	0.12 ± 0.03	25.0
$\sigma_D^{\rm nucleon}$ [μ b] [14]	30.1 ± 3.1	10.3
$Br\,(D_s \to \nu_\tau + \tau)$ [16]	0.07 ± 0.04	57.1
n [14]	4.9 ± 0.5	4.0
b [14]	1.0 ± 0.1	5.0
Spectra of ν_4 produced in τ decay	see text	5.0

Table 1: Values of the parameters used in the analysis and their contribution in percentage to the systematic error on the expected number of decay events (4). The uncertainty due to the knowledge of the spectra of ν_4 produced in τ decay refers to heavy neutrinos from reaction (3).

In equation (13) one has

$$\mathrm{BR}\,(D_s \to \nu_4 + \tau) = \mathrm{BR}\,(D_s \to \nu_\tau + \tau)\,\rho_{D_s}\,|U_{\tau 4}|^2 \quad . \tag{15}$$

The value of the branching ratio of the D_s decay into a zero mass neutrino, $\mathrm{BR}\,(D_s \to \nu_\tau + \tau)$, is reported in Table 1 [16]. Its uncertainty dominates the systematic error of this study. The factor ρ_{D_s} describes phase space and helicity effects [17]. In the case of τ decay into ν_4

$$\mathrm{BR}\,(\tau \to \nu_4 + ...) = |U_{\tau 4}|^2 \sum_i \mathrm{BR}\,(\tau \to \nu_\tau + X_i)\,\rho_\tau^i = \rho_\tau\,|U_{\tau 4}|^2 \quad , \tag{16}$$

where $\mathrm{BR}\,(\tau \to \nu_\tau + X_i)$ is the branching ratio of the τ decay into a zero mass neutrino according to the considered mode i [16], see Table 2, and the ρ_τ^i are factors depending on heavy neutrino mass. For i = 1–3 they take into account phase space and helicity effects [18]. For the modes 4–11 the ρ_τ^i's were computed using only

i	Mode	Branching ratio [%]
1.	$\tau \to \mu + \nu_\mu + \nu_\tau$	17.37
2.	$\tau \to e + \nu_e + \nu_\tau$	17.83
3.	$\tau \to \pi^- + \nu_\tau$	11.09
4.	$\tau \to \pi^- + \pi^0 + \nu_\tau$	25.40
5.	$\tau \to \pi^- + K^0 + \nu_\tau$	1.06
6.	$\tau \to \pi^- + 2\pi^0 + \nu_\tau$	9.13
7.	$\tau \to \pi^+ + 2\pi^- + \nu_\tau$	9.49
8.	$\tau \to \pi^- + 3\pi^0 + \nu_\tau$	1.21
9.	$\tau \to 2\pi^- + \pi^+ + \pi^0 + \nu_\tau$	4.32
10.	$\tau \to 2\pi^- + \pi^+ + K^0 + \nu_\tau$	1.35
11.	$\tau \to e + \gamma + \nu_e + \nu_\tau$	1.75

Table 2: The τ decay modes and corresponding branching ratio values used in the analysis

phase space [19]. The numerical values of ρ_τ^4 as a function of the neutrino mass are smaller than the ones of Ref. [20] by about 10%. The latter were obtained taking into account also helicity effects and the experimental width of the vector meson ρ.

For a given neutrino mass, the acceptances of the heavy neutrino flux coming from the D_s [τ], $A_{\nu_4}^{D_s}$ [$A_{\nu_4}^{\tau}$], and the corresponding energy spectrum normalized to one, $\phi_{\nu_4}^{D_s}(E_{\nu_4})$ [$\phi_{\nu_4}^{\tau}(E_{\nu_4})$] were obtained using a Monte Carlo simulation. The production of strange charm by protons was parametrized using the semi-empirical expression

$$f(x_F) \approx (1 - |x_F|)^n \, e^{-bp_{\mathrm{T}}{}^2} \quad , \tag{17}$$

where x_F is the meson longitudinal momentum in the collision center of mass frame divided by its maximum value $\sqrt{s}/2$, and p_{T} is the meson transverse momentum. Since there are few experimental results available on the production of $D_s^{\pm}$, the values of n and b were inferred from the measurements of D production. Assuming the hadronization process to be independent of the $c\bar{c}$ production mechanism, the parameters n and b are independent of the meson produced. Most measurements agree with a value of b equal to 1 $(\mathrm{GeV}/c)^{-2}$. The used values reported in Table 1 were obtained by the NA27 Collaboration studying the production of D's in the interactions of 400 GeV protons in an H_2 target [14]. Cascade production was neglected.

The energy spectrum of heavy neutrinos from τ decay is given by

$$\phi_{\nu_4}^{\tau}(E_{\nu_4}) = \frac{\sum\limits_{i=1}^{11} \rho_\tau^i \phi_{\nu_4}^i(E_{\nu_4})}{\sum\limits_{i=1}^{11} \rho_\tau^i} \quad , \tag{18}$$

where $\phi_{\nu_4}^i(E_{\nu_4})$ is the normalized energy distribution of neutrinos produced in the decay mode i (see Table 2). In the case of leptonic channels, $i = 1$ and 2, the spectra were obtained using the matrix element

$$|A|^2 \approx (p_\tau \cdot p_{\nu_l})\,(p_l \cdot p_{\nu_4}) \quad . \tag{19}$$

The quantities p_τ, p_{ν_l}, p_l and p_{ν_4} are the four-momenta of τ, light neutrino, electron or muon, and heavy neutrino, respectively. The spectrum of heavy neutrino produced by channel 11 was obtained using phase space. The multi–pion decay modes were simulated using two models. In model (a) the spectra of channels 4–10 and their relative contributions as a function of the heavy neutrino mass were computed using phase space [19]. In model (b) channel 4 was assumed to be produced through the resonance ρ and channels 5–10 through the resonance a_1. The resonances were assumed to have zero width. The ρ_τ^i's in (18) are given by:

$$\rho_\tau^i = \frac{(1-y)^2 + x\,(1+y-2x)}{1+x-2x^2} \sqrt{1 - y\left[\frac{2+2x-y}{(1-x)^2}\right]} \quad , \tag{20}$$

where $x = m_\rho^2 \big/ m_\tau^2$ for $i = 4$, (m_ρ = 770 MeV/c^2), $x = m_{a_1}^2/m_\tau^2$ for i = 5–10 (m_{a_1} = 1260 MeV/c^2) and $y = m_{\nu_4}^2/m_\tau^2$. The values of Table 3 were computed using the average of the spectra obtained in the two models. The systematic error in Table 1 reflects the differences of the spectra.

The decay (4) was simulated using the matrix element [8]

$$|A|^2 \approx \left[\tilde{g}_L^2\,(p_{\nu_4}\cdot p_{e^-})\,(p_{\nu_\tau}\cdot p_{e^+}) + g_R^2\,(p_{\nu_4}\cdot p_{e^+})\,(p_{\nu_\tau}\cdot p_{e^-})\right] \tag{21}$$

which neglects the electron mass. The quantities p_{e^-}, p_{e^+} and p_{ν_τ} are the four-momenta of electron, positron and tau neutrino, respectively. In the center of mass of the decaying heavy neutrino the four-vector p_{ν_4} is given by [21]

$$p_{\nu_4} = (m_{\nu_4},\, -m_{\nu_4}\,|h|\,\vec{\eta}) \quad , \tag{22}$$

where $\vec{\eta}$ is a unit vector parallel to the direction of the heavy neutrino in the rest frame of the particle decaying into neutrino, D_s, or τ, and $|h|$ is the absolute value of the neutrino (antineutrino) helicity. In the case of heavy neutrinos coming from D_s decay, the values of $|h|$ obtained in Ref. [16] were used. As the polarization of τ produced in D_s decay is negligible, $|h| = 0$ was assumed for the heavy neutrinos produced in τ decay. The acceptances and the mean momenta of decaying heavy neutrinos expected to be detected in the detector are reported in Table 3 for different values of neutrino mass. The efficiency of the cut $E_{\rm el} > 2$ GeV is about 85% for heavy neutrinos coming from D_s and larger than 95% for the ones coming from τ.

In Eq. (12) the probability for a heavy neutrino of energy E_{ν_4} to decay in the decay fiducial volume is given by

$$P_{\nu_4\to\nu_\tau e^+e^-}\,(E_{\nu_4}) = e^{-\frac{L}{\lambda}}\left(1 - e^{-\frac{D}{\lambda}}\right)\frac{\Gamma\,(\nu_4 \to \nu_\tau + e^+ + e^-)}{\Gamma_{\rm tot}} \quad , \tag{23}$$

where $\lambda = (\gamma\beta c)/\Gamma_{\rm tot}$ is the heavy neutrino mean decay path ($\gamma = E_{\nu_4}/m_{\nu_4}$, $\beta = p_{\nu_4}/E_{\nu_4}$). According to Eqs. (9) and (11) λ depends on $|U_{\tau 4}|^2\left(1 - |U_{\tau 4}|^2\right)$.

The quantity $\varepsilon\,(m_{\nu_4})$ in Eq. (12) is the efficiency of the selection criteria based on the regularity of the development of electromagnetic showers and the collinearity between the (two) shower(s) and the neutrino direction. The values, obtained using a detailed Monte Carlo simulation of the detector response, decrease with increasing heavy neutrino mass. It ranges from 91% for $m_{\nu_4} = 10\,\mathrm{MeV}/c^2$ to 65% for $m_{\nu_4} = 290\,\mathrm{MeV}/c^2$ [4].

Since no decay event was detected, upper limits at 90% confidence level on $|U_{\tau 4}|^2$ were obtained in the neutrino mass range 10–290 MeV/c^2. The limit value

m_{ν_4} [MeV/c^2]	$A_{\nu_4}^{D_s} \times 10^{-3}$	$\left\langle p_{\nu_4}^{D_s} \right\rangle$ [GeV]	$A_{\nu_4}^{\tau} \times 10^{-3}$	$\left\langle p_{\nu_4}^{\tau} \right\rangle$ [GeV]
10	3.39	14.39	3.49	47.14
50	3.50	14.14	3.54	47.13
100	4.11	12.90	3.61	46.86
150	6.00	10.39	3.73	46.48
190	8.00	8.38	3.87	46.44
250	-	-	4.04	46.03
290	-	-	4.24	45.62

Table 3: Acceptances and mean momenta of decaying heavy neutrinos with $E_{\text{el}} > 2$ GeV for different values of the neutrino mass.

of $N = N_l = 6.42$ events was used in Eq. (12). Since the contribution to the systematic error of the uncertainty on the spectra of heavy neutrinos coming from τ decay is negligible, N_l does not depend on the neutrino mass. It corresponds to an average probability of observing no events, $\langle P_0 (N_l) \rangle$, equal to 10% [22]:

$$\langle P_0 (N_l) \rangle = \int_{-\infty}^{+\infty} f\left(0;\, N_l'\right)\, W\left(N_l';N_l,\sigma\right)\, dN_l' = 0.1 \ , \tag{24}$$

where $f\left(0;\, N_l'\right) = e^{-N_l'}$ is the Poisson probability of obtaining zero events. In the case of negative N_l', $f\left(0;\, N_l'\right) = 1$ was used. The probability density function $W\left(N_l';N_l,\sigma\right)$ takes into accounts the systematic errors summarized in Table 1 and was assumed to be a Gaussian distribution. Combining in quadrature the uncertainties reported in the table, one gets $\sigma/N_l = 0.64$. In the case of no uncertainty, $W\left(N_l';N_l,\sigma\right) = \delta\left(N_l' - N_l\right)$ and the integral gives $N_l = 2.30$: the upper limit at 90% confidence level for the mean value of a Poisson distribution in the case of zero observations. The chosen value $N_l = 6.42$ is a safely conservative number: taking for instance $W\left(N_l';N_l,\sigma\right)$ equal to a log-normal distribution to avoid negative values of N_l' [22], one obtains $N_l = 3.21$, a factor 2 smaller than the value used in the analysis.

The upper limits obtained at 90% confidence level on $|U_{\tau 4}|^2$ values, as a function of m_{ν_4}, are shown in Fig.3, together with previous results [9], [23]. Limits on $|U_{\tau 4}|^2$ were also obtained for neutrino masses larger than 140 MeV/c^2 assuming $|U_{e4}|^2 = |U_{\mu 4}|^2 = |U_{\tau 4}|^2$ from the upper bounds on the rates of the decays $\tau^- \to e^{\pm}\left(\mu^{\pm}\right)\, \pi^{\mp}\pi^-$ [24]. Limits on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ are reported in Ref. [16].

In conclusion, the negative results of a search of decays of neutral particles into two electrons performed by the CHARM Collaboration in a neutrino beam dump experiment, allowed limits to be set at 90% c.l. on the square of the mixing strength, $|U_{\tau 4}|^2$, between ν_τ and a mostly isosinglet fourth neutrino, ν_4, having a mass in the range 10–290 MeV/c^2. Values of $\cong 10^{-4}$ were obtained for masses larger than 160 MeV/c^2.

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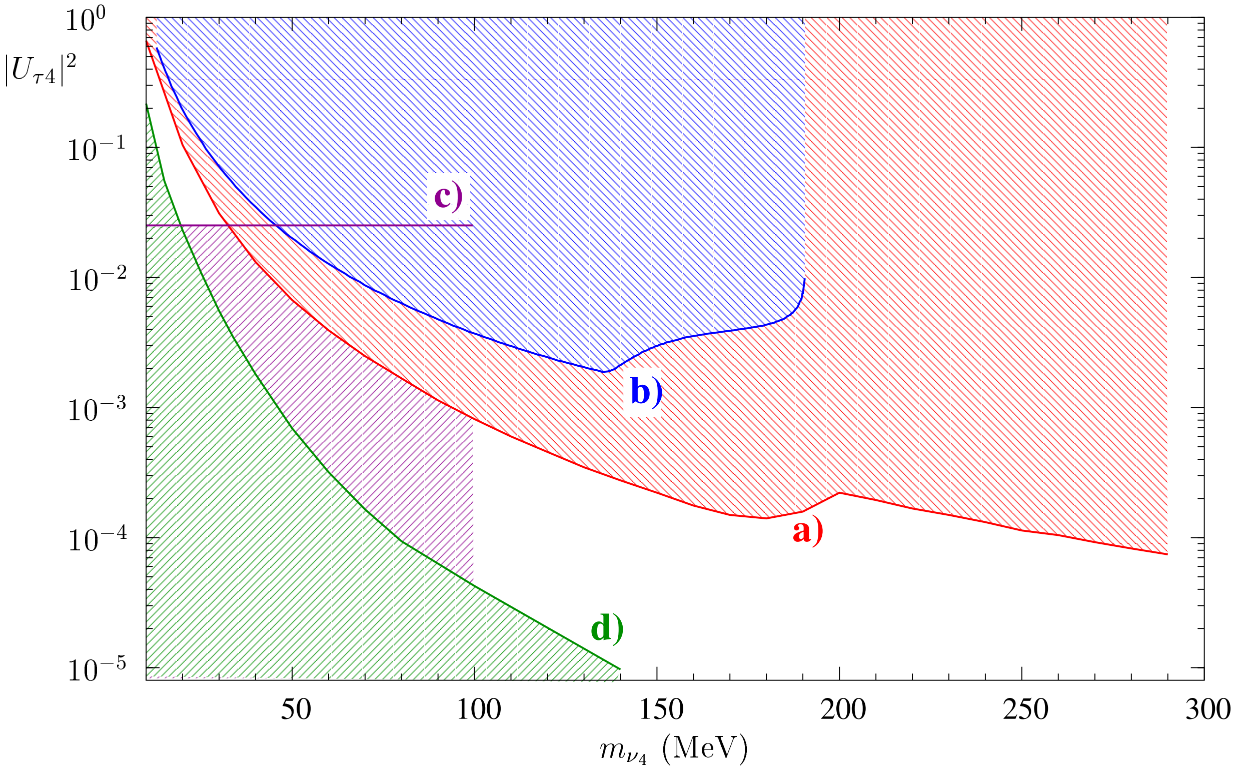

Figure 3: Limits at 90% confidence level on the square of the mixing strength $|U_{\tau 4}|^2$ of the τ-neutrino with a fourth neutrino mass eigenstate mostly isosinglet : (a) upper limits from this study; (b) the NOMAD upper limits [23]. The lower limits (c) from SN1987a and (d) from the Big Bang Nucleosynthesis constraint $\Delta N_\nu^{eff} \leq 0.2$ are reproduced from Ref. [9]. Note that the very small mixing angles for the corresponding mass range are allowed both by SN1987a ($|U_{\tau 4}|^2 \leq 10^{-8}$) and by BBN ($|U_{\tau 4}|^2 \leq 10^{-10} - 10^{-12}$) [9], because in this case the isosinglet neutrinos would not be produced in the sufficient quantities. All the limits were obtained assuming that neutrinos have Dirac masses ($K = 1$).

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