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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 $|U_{\tau 4}|^2$ of ν_τ to heavy neutrinos, ν_4's , with a mass in the range of 10-290 MeV/c^2 which are mostly isosinglet 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 produced by dumping 400 GeV proton in a *Cu* target. Upper limits $\cong 10^{-4}$ were obtained for neutrino masses greater than 160 MeV/c^2.

Neutrinos may have Dirac or Majorana masses. In general the mass eigenstate $(\nu_1, \nu_2, \nu_3, \nu_4, \ldots)$ 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 $|U_{\tau 4}|^2$of ν_τ with a heavy neutrino, ν_4, mostly isosinglet under the Standard $SU(2)_L$ gauge group and with a mass in the range $10 \leq m_{\nu_4} \leq 290\mathrm{MeV/c}^2$. 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 $3{\times}3$ m^2 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 $0.5X_0$ 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 $3.9{\times}10^{-5}$ 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.

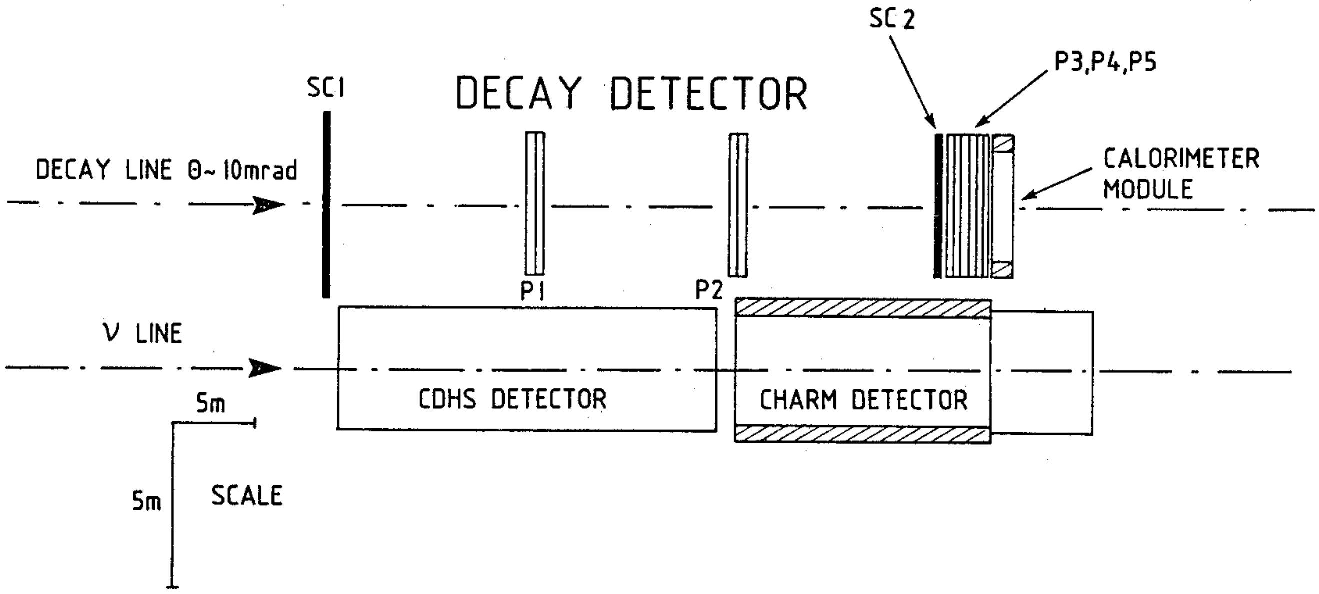

Figure 1: Layout of the decay detector.

The detector was exposed to a neutrino flux produced by $1.7{\times}10^{18}$ protons on a solid copper target [7] and $0.7{\times}10^{18}$ protons on a copper target laminated with an effective density of 1/3 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 4 out of the 6 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 2.5×2.5 m^2 surface area centred on the detector axis and that the electron energy E_{el} , measured in the calorimeter module, be $E_{el} > 2GeV$. The events recognised as cosmic rays were also rejected. The left 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 shower (showers) from the incoming beam one and the fraction of the energy detected by the proportional drift tubes of the calorimeter module outside a narrow cone around the shower for the decay events have been evaluated by a Monte Carlo method [4]. No event compatible with the features of the decay of a neutral particle into two electrons was found.

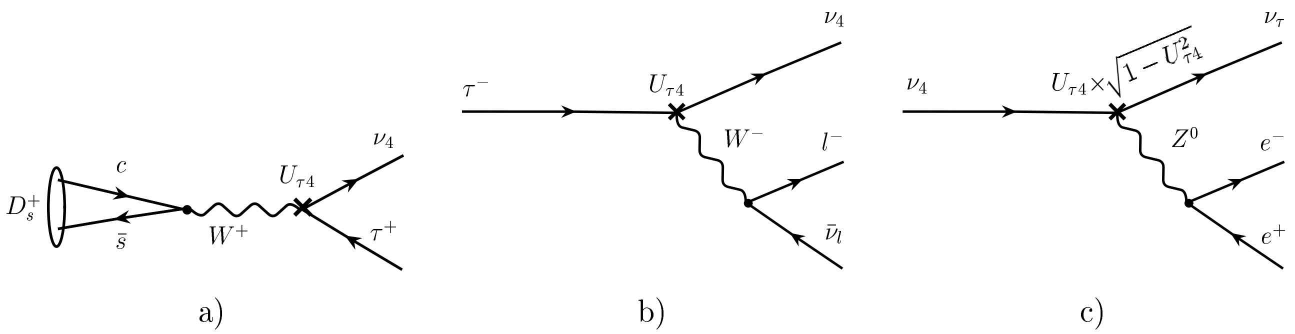

Figure 2: Feyman diagrams illustrating: a) ν_4 production from D_s, b) leptonic decay of τ^-, c) decay of an isosinglet neutrino ν_4 according to the mode (4).

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 a τ. The heavy neutrino is produced in the Charged Current decays

$$D_s \rightarrow \nu_4 + \tau \qquad (2)$$

and

$$\tau \rightarrow \nu_4 + ... \quad . \qquad (3)$$

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. 2 a) and b) respectively.

On the basis of the assumptions made, the isosinglet heavy neutrino decays only via Neutral Current interactions according to the modes

$$\nu_4 \rightarrow \nu_\tau + e^+ + e^- \qquad (4)$$

$$\nu_4 \rightarrow \nu_\tau + \nu_l + \bar{\nu}_l \quad (l = e, \mu \, \text{and} \, \tau) \qquad (5)$$

$$\nu_4 \rightarrow \nu_\tau + \mu^+ + \mu^- \qquad (6)$$

$$\nu_4 \rightarrow \nu_\tau + \pi^0 \quad . \qquad (7)$$

The Feynman diagram illustrating the signal decay channel (4) is shown in Fig. 2 c). 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

$$\Gamma_{tot} = \Gamma\left(\nu_4 \to \nu_\tau + \nu_l + \bar{\nu}_l\right) + \Gamma\left(\nu_4 \to \nu_\tau + e^+ + e^-\right) + \theta\left(m_{\nu_4} - m_{\pi^0}\right)\Gamma\left(\nu_4 \to \nu_\tau + \pi^0\right) \quad (8)$$

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

$$\Gamma\left(\nu_4 \to \nu_\tau + \nu_l + \bar{\nu}_l\right) + \Gamma\left(\nu_4 \to \nu_\tau + e^+ + e^-\right) = K\left[\frac{\left(1 + \tilde{g}_L^2 + g_R^2\right) G_F^2 m_{\nu_4}^5 \left|U_{\tau 4}\right|^2 \left(1 - \left|U_{\tau 4}\right|^2\right)}{192\pi^3}\right] \quad (9)$$

where $\tilde{g}_L = g_L - 1 = -1/2 + \sin^2\theta_w$ and $g_R = \sin^2\theta_w$, 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):

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

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

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

For a given heavy neutrino mass $m_{\nu_4}$the number of the decay events (4) expected in the detector is

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

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 shower (showers) and neutrino direction. The flux $\Phi\left(E_{\nu_4}\right)$ is given by

$$\Phi\left(E_{\nu_4}\right) = N_p \frac{\sigma_{D_s}}{\sigma_{inel}}\left[\begin{array}{l} Br\left(D_s \to \nu_4 + \tau\right) A_{\nu_4}^{D_s} \phi_{\nu_4}^{D_s}\left(E_{\nu_4}\right) + \\ +Br\left(D_s \to \nu_\tau + \tau\right) Br\left(\tau \to \nu_4 + \ldots\right) A_{\nu_4}^{\tau} \phi_{\nu_4}^{\tau}\left(E_{\nu_4}\right) \end{array}\right] \quad (13)$$

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 $N_p = 2.0\times 10^{18}$. The fraction of proton inelastic interactions leading to a charged D_s is given by [10]

$$\frac{\sigma_{D_s}}{\sigma_{inel}} = \frac{A_{Cu}\left[\sigma\left(D_s\right)/\sigma\left(D\right)\right]\sigma_D^{nucleon}}{\sigma_{inel}^{Cu}} = 2.98 \times 10^{-4}. \quad (14)$$

where the copper mass number is $A_{Cu} = 63.55$. Linear A dependence is assumed for charm production. The used values of the inelastic proton cross section, σ_{inel}^{Cu} [11], of the ratio of the production cross section for $D_s^\pm$ over the production cross section for $D^\pm + D^0$, $\sigma\left(D_s\right)/\sigma\left(D\right)$ [12], and of the inclusive cross sections for the production of D mesons, $\sigma_D^{nucleon}$ [13] are reported in Table 1. The ratio $\sigma\left(D_s\right)/\sigma\left(D\right)$ was obtained by the experiment Beatrice studying charmed particles produced by 350 GeV/c π^-'s [12]. It is compatible with the results obtained by e^+e^- experiments at centre-of-mass energies equal to 10 GeV and to the Z^0 mass [14]. The value of $\sigma_D^{nucleon}$ was obtained by the NA27 Collaboration studying the production of D's in the interactions of 400 GeV protons in a H_2 target [13].

Parameters	Values	Systematic errors [%]
σ_{inel}^{Cu} [mb][11]	769 ± 23	3.0
$\sigma\,(D_s)/\sigma\,(D)$[12]	0.12 ± 0.03	25.0
$\sigma_D^{nucleon}$ [μ b][13]	30.1 ± 3.1	10.3
$Br\,(D_s \to \nu_\tau + \tau)$[16]	0.07 ± 0.04	57.1
n[13]	4.9 ± 0.5	4.0
b[13]	1.0 ± 0.1	5.0
Spectra of ν_4 produced in τ decay	Phase space / Narrow resonances (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).

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 branching ratio values used in the analysis

The branching ratio of the decay (2) appearing in equation (13) is given by

$$Br\left(D_s \rightarrow \nu_4 + \tau\right) = Br\left(D_s \rightarrow \nu_\tau + \tau\right) \rho_{D_s} \left|U_{\tau 4}\right|^2 \tag{15}$$

where $Br\left(D_s \rightarrow \nu_\tau + \tau\right)$ is branching ratio of the D_s decay into a zero mass neutrino and ρ_{D_s} is the phase space and helicity factor [15]. The value of $Br\left(D_s \rightarrow \nu_\tau + \tau\right)$ is reported in Table 1 [16]. Its uncertainty dominates the systematic error of the study. In equation (13), the branching ratio of the τ decay into a ν_4 is given by

$$Br\left(\tau \rightarrow \nu_4 + ...\right) = \left|U_{\tau 4}\right|^2 \sum_i Br\left(\tau \rightarrow \nu_\tau + X_i\right) \rho_\tau^i = \rho_\tau \left|U_{\tau 4}\right|^2 \tag{16}$$

where $Br\left(\tau \rightarrow \nu_\tau + X_i\right)$ is the branching ratio of the τ decay into a zero mass neutrino according to the considered mode i [16] (see Table 2), and ρ_τ^i are factors depending on heavy neutrino mass. For $i =$ 1-3 the factors taking into account phase space and helicity effects [17] were used. For the modes 4-11 the ρ_τ^i were computed using phase space [18]. The derived numerical values of ρ_τ^4 as a function of the neutrino mass are smaller than the ones of Ref. [19] obtained taking into account helicity effects and the experimental width of the vector meson ρ of about 10%.

For a given neutrino mass, the acceptances of the heavy neutrinos fluxes coming from the D_s [τ], $A_{\nu_4}^{D_s}$ [$A_{\nu_4}^{\tau}$], and the corresponding energy spectrum normalised to one, $\phi_{\nu_4}^{D_s}\left(E_{\nu_4}\right)$ $\left[\phi_{\nu_4}^{\tau}\left(E_{\nu_4}\right)\right]$, were obtained using a Monte Carlo simulation. The distribution in kinematics quantities of strange charm hadroproduction was parameterised using the semi-empirical expression

$$f\left(x_F\right) \approx \left(1 - \left|x_F\right|\right)^n e^{-bp_T^2} \tag{17}$$

where x_F is the meson longitudinal momentum in the collision centre-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 hadronisation process 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 a H_2 target [13]. Cascade production was neglected.

The energy spectra of heavy neutrinos from τ decay are given by

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

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

$$\left|A\right|^2 \approx \left(p_\tau \cdot p_{\nu_l}\right) \left(p_l \cdot p_{\nu_4}\right) \tag{19}$$

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 [18]. In model b) channel 4 was assumed to be produced trough the resonance ρ and channels 5-10 trough the resonance a_1. The resonances were assumed to have zero width. Theρ_τ^i's in (18) are given by:

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

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 was estimated using in the simulation the spectra obtained applying the models *a*) and *b*).

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 centre-of-mass of the decaying heavy neutrino the four-vector p_{ν_4} is given by [20]

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

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. [15] were used. As the polarisation 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 $E_{el} > 2$ GeV is about 85% for heavy neutrinos coming from D_s and larger than 95% for the ones coming from τ.

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

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

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

The quantity $\varepsilon\,(m_{\nu_4})$ in equation (12) is the efficiency of the selection criteria based on the regularity of the development of electromagnetic showers and the collinearity between the shower (showers) 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 of $N = N_l = 6.42$ events was used in equation (12). Since the contribution to the systematic error of the uncertainty on the spectra of heavy neutrinos coming from τ decay is negligible, it does not depends on the neutrino mass and corresponds to an average probability of observing no events, $\langle P_0\,(N_l)\rangle$, equal to 10% [21]:

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

where $f\,(0;\,N_l') = e^{-N_l'}$ is the Poisson probability to get zero events. In the case of negative N_l' we used $f\,(0;\,N_l') = 1$. The probability density function $W\,(N_l';N_l,\sigma)$ takes into accounts the systematic errors summarised in Table 1 and was assumed to have a Gaussian form. Combining

$m_{\nu_4}\,[\mathrm{MeV}/c^2]$	$A^{D_s}_{\nu_4} \times 10^{-3}$	$\left\langle p^{D_s}_{\nu_4} \right\rangle$ [GeV]	$A^{\tau}_{\nu_4} \times 10^{-3}$	$\left\langle p^{\tau}_{\nu_4} \right\rangle$ [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 expected to be detected in the detector for different values of neutrino mass.

in quadrature the uncertainties reported in the table one gets $\sigma/N_l = 0.64$. The integral (24) was performed numerically. 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 a log-normal distribution to avoid negative values of N [21] would for instance give a tighter $N_l = 3.21$, a factor 2 better than reported here.

The obtained upper limits 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, 22]. Limits on $|U_{\tau 4}|^2$ were also obtained using the upper bounds on the rates of the decays $\tau^- \to e^{\pm}\,(\mu^{\pm})\ \pi^{\mp}\pi^-$ assuming $|U_{e4}|^2 = |U_{\mu 4}|^2 = |U_{\tau 4}|^2$ [23]. 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 to set limits at 90% *c.l.* on the square of the mixing, $|U_{\tau 4}|^2$, of ν_τ to a hypothetical 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 greater than $160\,\mathrm{MeV}/c^2$.

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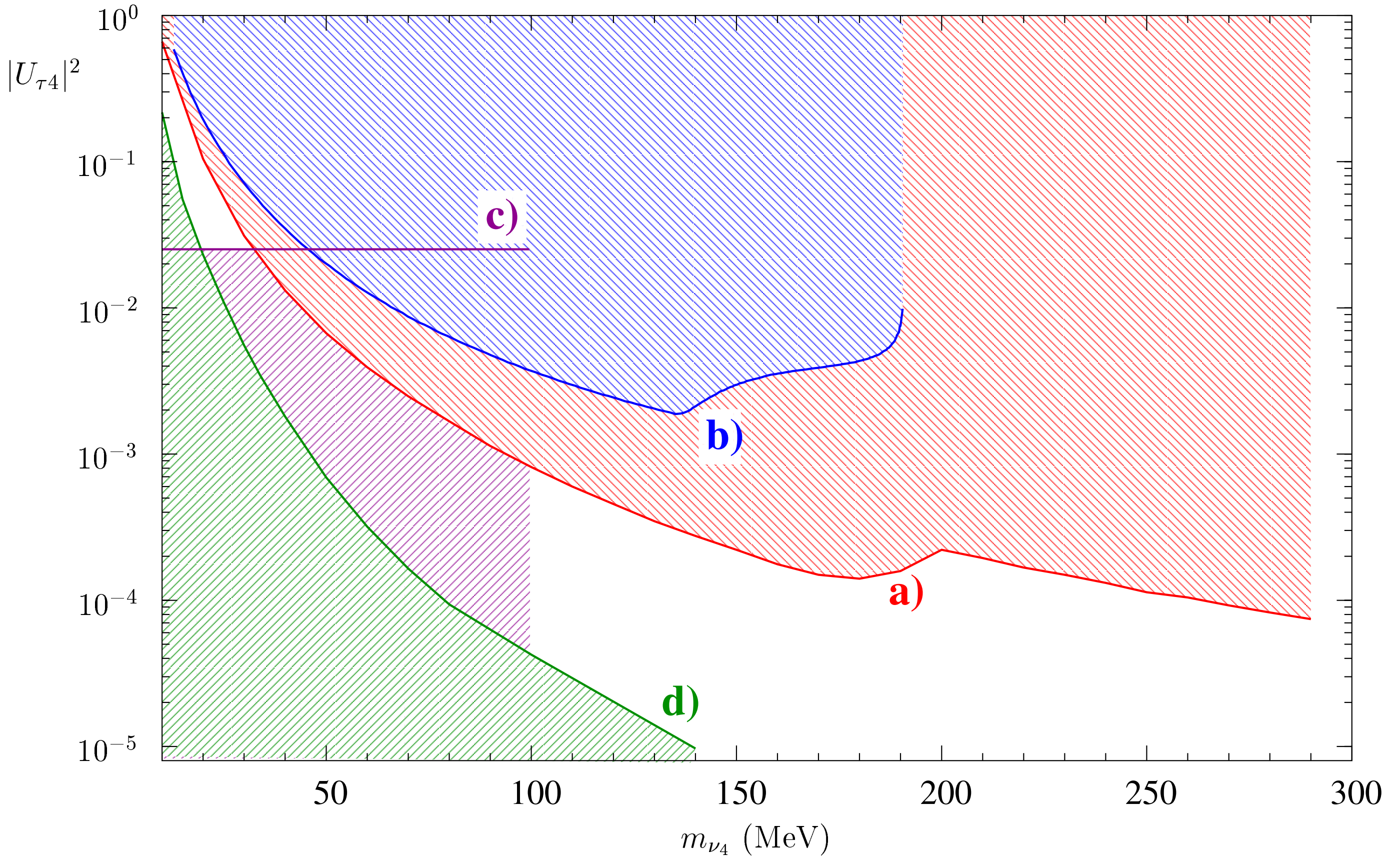

Figure 3: Limits at 90% confidence level on the mixing $|U_{\tau 4}|^2$ of the τ-neutrino with a fourth neutrino mass eigenstate: a) upper limits from this study; b) the NOMAD upper limits [22]. The lower limits c) from SN1987a and d) from the Big Bang Nucleosynthesis constraint $\Delta N_\nu^{eff} \leq 0.2$ are reproduced from Ref. [9]. Upper limits of $|U_{\tau 4}|^2 \leq 10^{-8}$ from SN1987a and of $|U_{\tau 4}|^2 \leq 10^{-10} - 10^{-12}$ from Big Bang Nucleosynthesis have also been derived for the corresponding mass range shown, respectively [9]. All the limits were obtained assuming that neutrinos have Dirac masses ($K = 1$).

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