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To cite this version:

Jean Orloff, A. Rozanov, C. Santoni. Limits on the square of the coupling strength of tau neutrino to isosinglet heavy neutrinos. 2002, pp.1-11. in2p3-00011797

HAL Id: in2p3-00011797
http://hal.in2p3.fr/in2p3-00011797

Submitted on 18 Jul 2002

PCCF-RI-0205
15/07/2002

LIMITS ON THE SQUARE OF THE COUPLING STRENGTH OF TAU NEUTRINO TO ISOSINGLET HEAVY NEUTRINOS

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Limits at 90% *c.l.* on the square of the coupling strength $|U_{\tau 4}|^2$ of ν_τ to a isosinglet heavy neutrino, ν_4 , with a mass in the range of 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 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

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

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 coupling strength $|U_{\tau 4}|^2$ of ν_τ to a heavy neutrino, ν_4, 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 3×3 m^2 surface area defined by a veto scintillator plane (*SC*1) and a scintillator hodoscope (*SC*2). The volume was subdivided into three regions using two sets of four proportional tube planes (*P*1 and *P*2) [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 (*P*3, *P*4 and *P*5) were installed in front of the module. Lead converters of $0.5X_0$ each were placed in front of *P*1, *P*2, *P*4 and *P*5. 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.

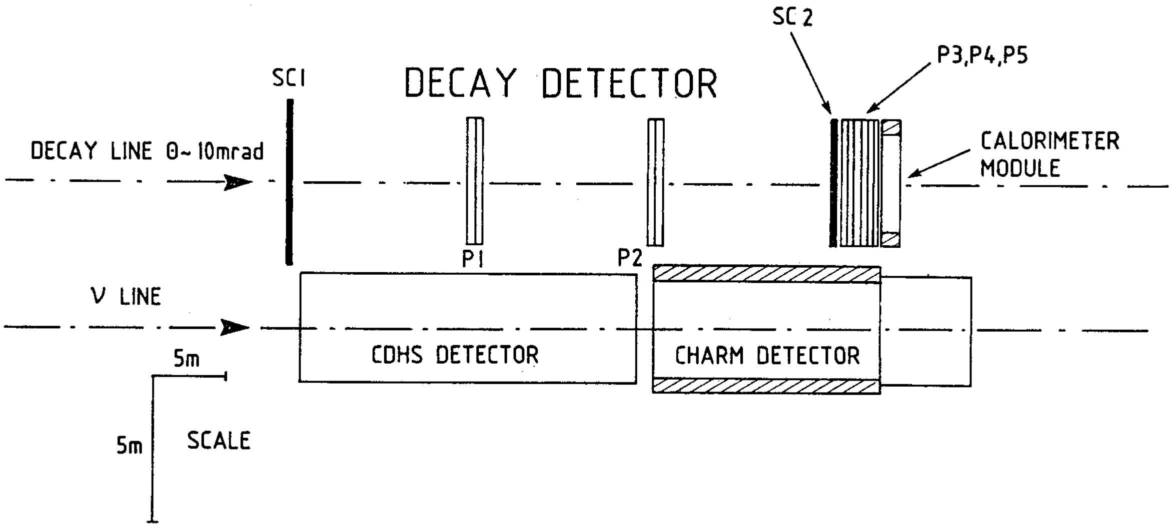

Fig. 1 Layout of the decay detector.

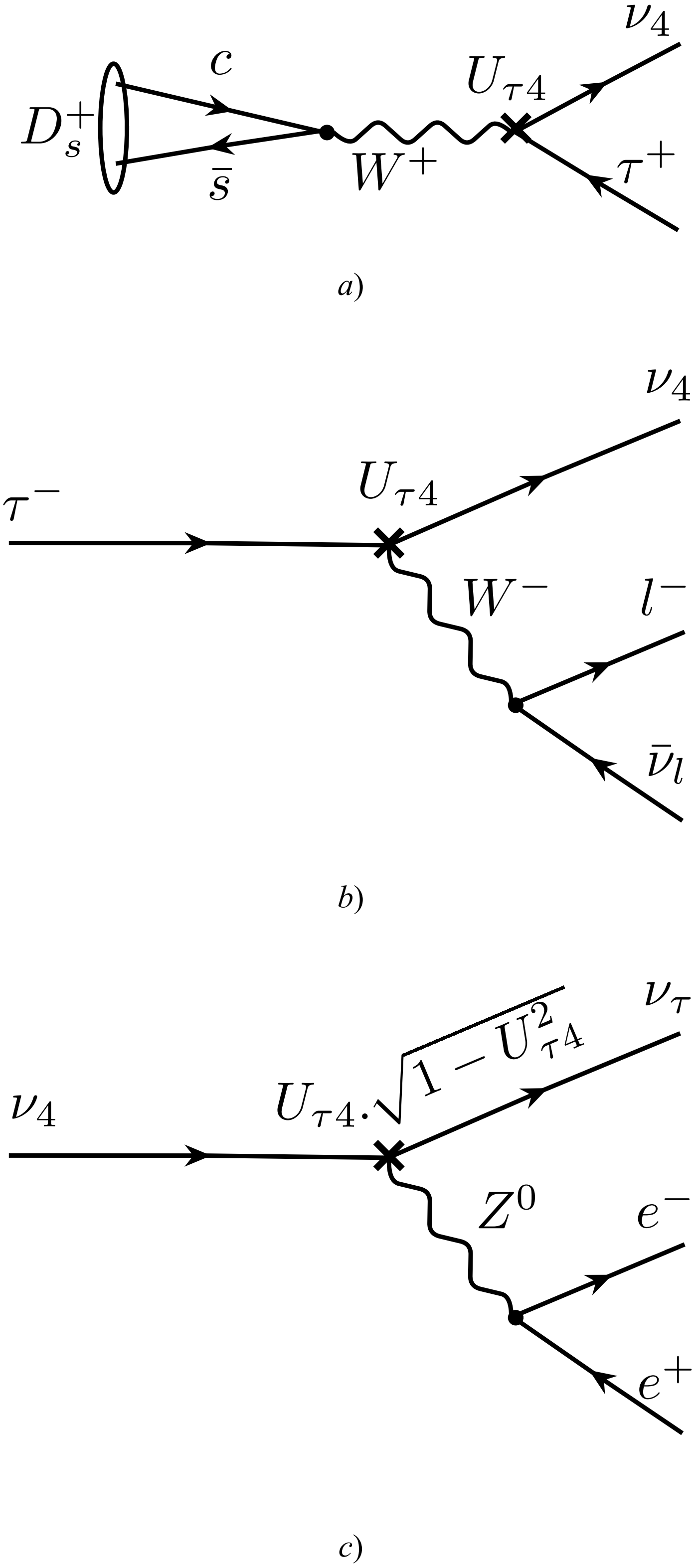

Fig. 2 Feyman diagrams illustrating: *a*) ν_4 production from D_s, *b*) leptonic decay of τ^-, *c*) decay of an isosinglet neutrino ν_4 according to the mode (4).

The detector was exposed to a neutrino flux produced by 1.7×10^{18} 400 GeV protons on a solid copper target [7] and 0.7×10^{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 $E_{el} > 2$ GeV. 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 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 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.

In the analysis we assumed that the ν_4, couples essentially with the ν_τ.It is produced by the Charged Current decays :

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

and

$$\tau \to \nu_4 + \dots \qquad (3)$$

The protons dumped on the target. produce the D_s's that decay into τ's. The Feynman diagrams of the process (2) and of the decay $\tau^- \to \nu_4 + l^- + \overline{\nu}_l$ ($l = e, \mu$) are shown in Fig. 1*a*) and 1*b*) respectively.

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

$$\nu_4 \to \nu_\tau + e^+ + e^- \qquad (4)$$
$$\nu_4 \to \nu_\tau + \nu_l + \overline{\nu}_l \quad (l = e, \mu \text{ and } \tau) \qquad (5)$$
$$\nu_4 \to \nu_\tau + \mu^+ + \mu^- \qquad (6)$$
$$\nu_4 \to \nu_\tau + \pi^0 \ . \qquad (7)$$

The Feynman diagram illustrating the signal decay channel (4) is shown in Fig. 1 *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

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

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

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

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):

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

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

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

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

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

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

$$\Phi(E_{\nu_4}) = N_p \frac{\sigma_{D_s}}{\sigma_{inel}} \begin{bmatrix} Br(D_s \to \nu_4 + \tau) A_{\nu_4}^{D_s} \phi_{\nu_4}^{D_s}(E_{\nu_4}) + \\ + Br(D_s \to \nu_\tau + \tau) Br(\tau \to \nu_4 + \ldots) A_{\nu_4}^{\tau} \phi_{\nu_4}^{\tau}(E_{\nu_4}) \end{bmatrix} \qquad (13)$$

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

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

where the copper mass number is $A_{Cu} = 63.55$. The used values of the inelastic proton cross section, σ_{inel} [11], of the ratio of the production cross section for $D_s^{\pm}$ over the production cross section for $D^{\pm} + D^0$, $\sigma(D_s)/\sigma(D)$ [12], and of the inclusive cross sections for the production of D mesons, $\sigma_D^{nucleon}$ [13] are reported in Tab.1. The ratio $\sigma(D_s)/\sigma(D)$ was obtained by the experiment Beatrice studying charmed particles produced by 350 GeV/c π^- [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].

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).

Parameters	Values	Systematic errors [%]
σ_{inel} [mb] [11]	769 ± 23	3.0
$\sigma(D_s)/\sigma(D)$ [12]	0.12 ± 0.03	25.0
$\sigma_D^{nucleon}$ [μb] [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 2 : The τ decay modes and branching ratio values used in the analysis

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

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

$$Br(D_s \to \nu_4 + \tau) = Br(D_s \to \nu_\tau + \tau)\rho_{D_s}|U_{\tau 4}|^2 \qquad (15)$$

where $Br(D_s \to \nu_\tau + \tau)$ is branching ratio of the D_s decay into a zero mass neutrino and ρ_{Ds} is the phase space and helicity factor [15]. The value of $Br(D_s \to \nu_\tau + \tau)$ is reported in Tab. 2 [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

$$Br(\tau \to \nu_4 + ...) = |U_{\tau 4}|^2 \sum_i Br(\tau \to \nu_4 + X_i)\rho_\tau^i = \rho_\tau |U_{\tau 4}|^2 \qquad (16)$$

where $Br(\tau \to \nu_\tau + X_i)$ is the branching ratio of the τ decay into a zero mass neutrino according to the considered mode *i* [16] (see Tab. 2), and ρ_τ^i are factors depending on heavy neutrino mass. For *i* = 1-3 the used factors take into account phase space and helicity [17]. For the modes 4-11 only phase space effects appear in the expressions of ρ_τ^i [18]. The 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.

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, $\phi_{\nu_4}^{D_s}(E_{\nu_4})$ $[\phi_{\nu_4}^{\tau}(E_{\nu_4})]$, were obtained using a Monte Carlo simulation. The distribution in kinematics quantities of strange charm hadroproduction was parameterised using the semi-empirical expression

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

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 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 (GeV/c)$^{-2}$. The used values reported in Tab. 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.

In the simulation of the τ decay, the spectra of heavy neutrinos produced in the leptonic modes *i* = 3 and 4 were obtained using the matrix element

$$|A|^2 \approx (p_\tau \cdot p_{\nu_l})(p_l \cdot p_{\nu_4}) \qquad (18)$$

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 relative contribution of the modes 1-3 was computed using the formulas of reference [17]. 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. The relative contributions were computed using the formula:

$$\rho_{\tau\to VM+\nu_4}(x,y)=\frac{(1-y)^2+x(1+y-2x)}{1+x-2x^2}\sqrt{1-y\left[\frac{2+2x-y}{(1-x)^2}\right]} \qquad (19)$$

where $VM = \rho$ or $a_1, x=m_{VM}^2/m_\tau^2$ (m_ρ=770 MeV/c^2, m_{a_1}=1260 MeV/c^2) and $y=m_{\nu_4}^2/m_\tau^2$. The spectrum of heavy neutrino produced by channel 11 and its relative contribution was obtained using phase space. The values of Tab. 3 were computed using the average of the spectra obtained in the two models. The systematic error in Tab.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]

$$|A|^2 \approx \left[\tilde{g}_L^2\left(p_{\nu_4}\cdot p_{e^-}\right)\left(p_{\nu_\tau}\cdot p_{e^+}\right)+g_R^2\left(p_{\nu_4}\cdot p_{e^+}\right)\left(p_{\nu_\tau}\cdot p_{e^-}\right)\right] \qquad (20)$$

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-momentum p_{ν_4} is given by [20]

$$p_{\nu_4}=\left(m_{\nu_4},-m_{\nu_4}|h|\vec{\eta}\right) \qquad (21)$$

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 Tab. 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

$$P_{\nu_4\to\nu_\tau e^+e^-}\left(E_{\nu_4}\right)=e^{-\frac{L}{\lambda}}\left(1-e^{-\frac{D}{\lambda}}\right)\frac{\Gamma\left(\nu_4\to\nu_\tau+e^++e^-\right)}{\Gamma_{tot}} \qquad (22)$$

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

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 axis 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].

Table 3 : Acceptances and mean momenta of decaying heavy neutrinos expected to be detected in the detector for different values of neutrino mass.

$m_{\nu_4}\left[\mathrm{GeV/c^2}\right]$	$A_{\nu_4}^{D_s} \times 10^{-3}$	$\left\langle p_{\nu_4}^{D_s}\right\rangle[\mathrm{GeV}]$	$A_{\nu_4}^{\tau} \times 10^{-3}$	$\left\langle p_{\nu_4}^{\tau}\right\rangle[\mathrm{GeV}]$
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

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 $N = N_l = 6.42$ was used in equation (12). It does not depends on the neutrino mass and corresponds to a probability of observing no events, $P_0(N_l)$, equal to 10% [21] :

$$P_0(N_l) = \int_{-\infty}^{0} W(N_l';N_l,\sigma)dN_l' + \int_{0}^{+\infty} e^{-N_l'} W(N_l';N_l,\sigma)dN_l' = 0.1 \ . \qquad (23)$$

The probability density function $W(N_l';N_l,\sigma)$ takes into accounts the systematic errors summarised in Tab. 1 and was assumed to have a gaussian form. Combining in quadrature the uncertainties reported in the table one gets $\sigma/N_l = 0.64$. The integral (20) was performed numerically. In the case of no uncertainty $W(N_l';N_l,\sigma) = \delta(N_l' - N_l)$ 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 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]. The results of this analysis are consistent with previous ones obtained by the CHARM collaboration [1, 2].

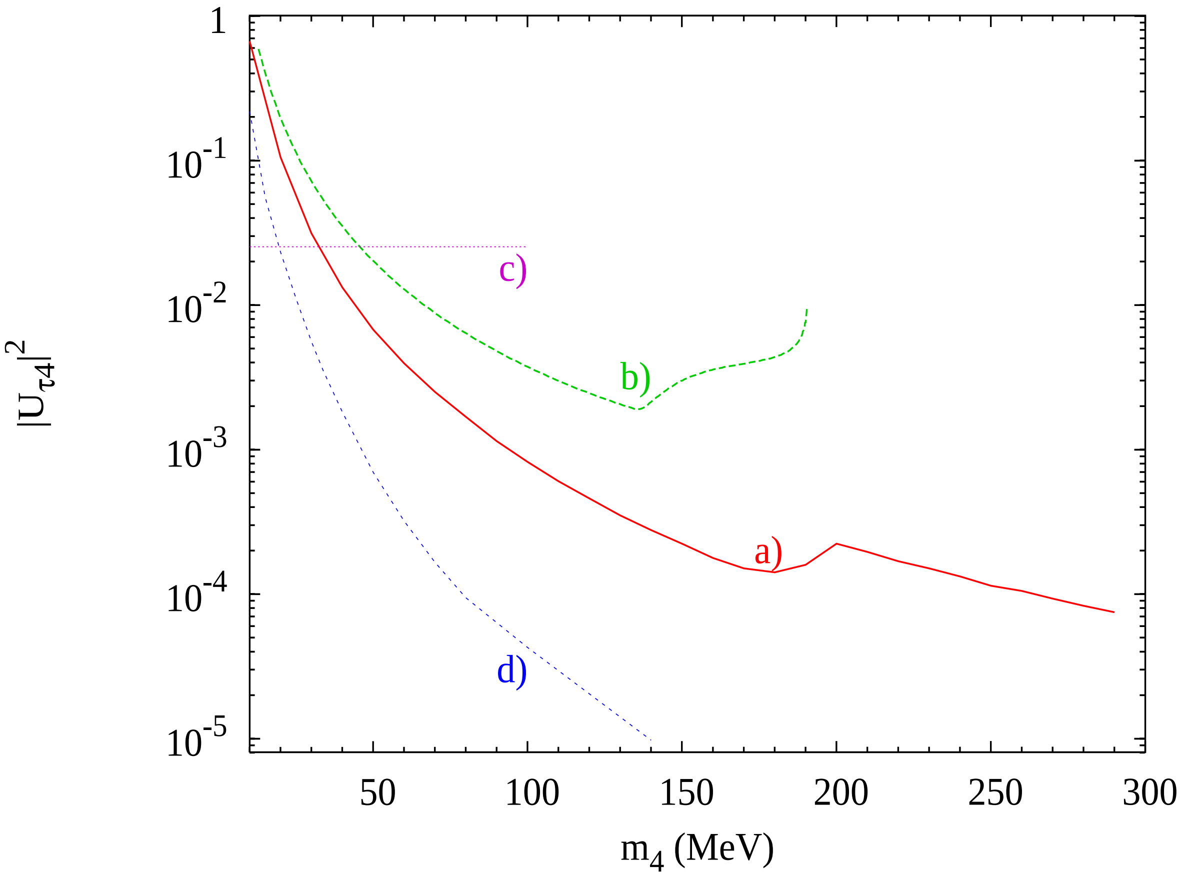

Fig. 3 Limits at 90% confidence level on $|U_{\tau 4}|^2$ (the square of the coupling strength of tau-neutrino weak eigenstate to mass eigenstate 4): *a*) upper limits from this study; *b*) the NOMAD upper limits [22]; the *SN*1987*a c*) and Big Bang Nucleosynthesis *d*) lower limits are reproduced from Ref. [9]. The neutrinos were assumed to have Dirac masses ($K = 1$).

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 coupling strength, $|U_{\tau 4}|^2$, of ν_τ to isosinglet neutrinos having a mass in the range 10-290 MeV/c^2. Values of $\cong 10^{-4}$ were obtained for masses greater than $160\,\mathrm{MeV/c^2}$.

We would like to thank the members of the CHARM Collaboration that allowed us to use their data. We would like to thanks B. Van de Vyver that allowed us to use his program for the generation of prompt neutrinos. We would like to thanks G. Barbiellini, L. Di Lella, A.D. Dolgov, S.N. Gninenko, S.H. Hansen, P. Loverre, M. Mangano and K. Winter for discussions.

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