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Neutrino Oscillation Experiments at CERN *

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Abstract

Recent results of a search for heavy isosinglet neutrinos and for ν_μ - ν_τ oscillation by the CHARM-II Collaboration are reported. The concepts and the status of the new experiments, CHORUS and NOMAD, searching for the appearance of ν_τ in a ν_μ beam are described. A new neutrino beam directed at the Gran Sasso laboratory for searching ν_e - ν_μ and ν_μ - ν_τ oscillations is under study at CERN.

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1. INTRODUCTION

From measurements at LEP we know that there exist three families of light neutrinos in nature. Do these neutrinos have non-zero mass? Do these families mix or are they distinct? Do heavy isosinglet neutrinos exist in nature? These questions belong to the most fundamental ones for experimental particle physics. Answers may come from searches for neutrino oscillation and from searches for decays of heavy neutrinos. The mixing of neutrino families can be described by a matrix, similar to the Cabibbo-Kobayashi-Maskawa matrix for quarks. Assuming neutrino masses are generated by a see-saw mechanism, and that the mass scale defined by a very heavy Majorana neutrino is the same for the three families, oscillation will be dominantly a phenomenon between the families of the two heaviest leptons, the muon and the tau. The wave length of the oscillation term is given by the difference of the neutrino masses squared, Δm^2 (eV^2), the neutrino energy, E_ν (GeV) and the distance between the neutrino source and the detector, L (Km). The probability of appearance of neutrinos of a new flavour, ν_b , in a beam of ν_a is given by the well-known expression,

$$P_{ab} = \sin^2 2\theta_{ab} \sin^2(1.27(L/E_\nu)\Delta m_{ab}^2) \quad (1)$$

where θ is the mixing parameter between families a and b .

Results from recent experiments on solar neutrinos, which are reported elsewhere at the conference, are consistent with a Mikheyev-Smirnov-Wolfenstein solution to the solar neutrino problem [1]. One of the favoured solutions gives a mass of ~ 3 milli eV to the ν_μ and through the see-saw mechanism a mass to the ν_τ ($m_{\nu_\tau} \sim 10$ eV) which would make it a candidate for dark matter [2]. Recent results on the anisotropy of the cosmic background radiation favour $m_{\nu_\tau} \sim 7$ eV.

2. SEARCH FOR HEAVY ISOSINGLET NEUTRINOS

We have to explore experimentally which neutrino states exist in nature. The LEP experiments [3] have determined the number of light isodoublet neutrinos $N_\nu = 2.90 \pm 0.027$. Isosinglet neutrinos have no weak interactions except those induced by mixing with isodoublet neutrinos. Experimental searches of heavy isosinglet neutrinos, ν_H , which mix with muon neutrinos, have been performed in meson decay experiments: $\pi \rightarrow \mu \nu_H$ [4], $K \rightarrow \mu \nu_H$ [5, 15], $D \rightarrow \mu \nu_H$ [6] and in e^+e^- experiments: $e^+e^- \rightarrow Z \rightarrow \nu_\mu \nu_H$ [7].

The mass range accessible by the meson decay experiments is limited by the mass of the parent mesons, but e^+e^- experiments have extended limits for neutrino masses to above 5 GeV. The intermediate mass range from 0.3 to 2.5 GeV can be covered by producing ν_H in a neutral current (NC) reaction induced by ν_μ :

$$\nu_\mu N \rightarrow \nu_H X \quad . \quad (2)$$

The coupling between ν_μ and ν_H and that of μ and ν_H is described by a mixing parameter $|U_{\mu H}|^2$ relative to the Fermi-coupling constant. Previous searches using this concept have been performed by the CHARM Collaboration [8] and by the CCFR Collaboration [9]. A new search has been performed by the CHARM II Collaboration [10] using a 100 times larger statistical sample and a new method to separate ν_H decay events from background.

The signature for the ν_H search is a two vertex event. The first vertex is the NC reaction producing the ν_H and the second vertex is the decay of the ν_H . The sensitivity of the experiment depends mainly on the background which can be reduced by the choice of the decay channel and on the minimum detectable distance between the two vertices.

Background arises from random overlays of two independent neutrino interactions in the sensitive time of the detector and from double events where the second vertex is due to the interaction of a neutron or the decay of a neutral kaon originating from the NC event at the first vertex. The decay mode $\nu_H \rightarrow \mu^+ \mu^- \nu_\mu$ with a branching ratio of 5-7% for m_{ν_H} 1-3 GeV which we selected gives a 10^5 times smaller random background than the dominant decay $\nu_H \rightarrow (\text{hadrons } \nu_\mu)$ with a branching ratio of $\sim 50\%$. The background from neutrons or K's originating from the NC vertex is important for ν_H decays into hadrons but negligible for the two-muon topology. The trigger selected events with two muons and low hadronic activity at the vertex. Events preceded by a NC event were selected in a fiducial volume. In a total sample of $2 \cdot 10^7$ ν_μ and $\bar{\nu}_\mu$ NC events ten such events were found, one is shown in figure 1. The double vertex process is kinematically constrained by eight equations of energy and momentum conservation. The invariant mass of the hadron shower of the NC event was determined by a new method based on its correlation with the energy transverse to the shower direction [10]. Six kinematical quantities are unmeasured: the energy of the incoming neutrino, the mass and energy of the decaying ν_H and the momentum vector of the ν_μ from ν_H decay. The kinematics is thus over-determined

Figure 1. One candidate event for $\nu_\mu N \rightarrow \nu_H X$, $\nu_H \rightarrow \mu^+ \mu^- \nu_\mu$.

by two degrees of freedom which were used to test if the data can satisfy the kinematical

hypothesis of ν_H production and subsequent decay. None of the candidates satisfied this kinematical fit. The efficiency of this fit was tested with MC events.

The sensitivity in terms of the mixing parameter $|U_{\mu H}|^2$ was calculated taking into account the threshold effects due to the mass of the heavy neutrino and the efficiency of recognising double events by their topology and kinematics in the fiducial volume of the detector. In conclusion, there is no evidence for heavy neutrinos in the mass range 0.3 to 2.5 GeV, the 90% C.L. for $|U_{\mu H}|^2$ is smaller than $3 \cdot 10^{-5}$ at ~ 2 GeV. Figure 2 shows this result together with earlier results.

Figure 2. 90% confidence limits for the mixing parameter $|U_{\mu H}|^2$ derived from searches for heavy isoscalar neutrinos: a) [8], b) [8], c) [4], d) [5], e) [15], f) [6], g) [7].

3. SEARCH FOR $\nu_\mu - \nu_\tau$ OSCILLATION

A search for appearance of tau neutrinos in a beam of muon neutrinos requires detection of the reaction

$$\nu_\tau N \rightarrow \tau^- X \quad (3)$$

in a background of ν_μ induced reactions. The prompt background of ν_τ is mainly produced through the decay of D_s mesons. At the 450 GeV CERN-SPS the flux ratio of $\Phi(\nu_\tau)/\Phi(\nu_\mu) < 10^{-7}$ is very favourable for a sensitive search for ν_τ appearance. The proton energy, the geometry of the horn focussing and the minimal distance to the detector determine the mean neutrino energy, $E_\nu \sim 27$ GeV, the mean distance from the neutrino source to the detector, $L \sim 600$ m and thereby the domain of $\Delta m^2 > 1$ eV.

There are several concepts for the detection of reaction (3). The most direct way is observation of the τ decay topology. The mean life of $3 \cdot 10^{-13}$ s leads to a mean decay length in the experiment of $\sim 100 \mu\text{m}$. This concept has been adopted by the CHORUS Collaboration [11]. Another way of discrimination is by the apparent non-conservation of transverse momentum owing to the undetected neutrino in τ decays. This concept, originally proposed by Albright and Shrock [12] has been adopted by the NOMAD Collaboration [13].

Yet another way has been used by the CHARM II Collaboration [14]. Quasi-elastic ν_τ interactions are searched for in which the tau lepton decays into $\tau^- \rightarrow \pi^- \nu_\tau$. These events appear in the fine-grain calorimeter of the CHARM II detector as a single track followed by a shower created by its interaction. Requiring a minimum track length of 15 planes of the detector ($\sim 1.7 \lambda_{\text{abs}}$) and a shower energy greater than 10 GeV they found 124 candidates. Fitting the kinematical distributions in shower energy E_s and in the transverse shower energy $E_s \cdot \theta_t$ where θ_t is the single track direction to the sum of contributions from the ν_τ reaction and from the background reaction $\nu_\mu N \rightarrow \nu_\mu \pi^+ N'$ which were simulated by Monte Carlo methods, they derived the 90% confidence exclusion region shown in figure 3 together with earlier results. The sensitivity of $\sin^2 2\theta_{\mu\tau} > 6.4 \cdot 10^{-3}$ for $\Delta m^2 > 50 \text{ eV}^2$ comes close to the

result of the Fermilab experiment E531. The estimated sensitivity of the CHORUS and NOMAD experiments are shown for comparison. These experiments have the sensitivity required to eliminate the possibility that most of the mass of the universe is carried by tau neutrinos.

Figure 3. Exclusion plot (90% C.L.) for ν_μ - ν_τ oscillation showing results from E531 [17], CHARM II [14], CCFR [18], CDHS and CHARM [19] and the new domain which is being explored by CHORUS [11] and NOMAD [13].

4. NEW EXPERIMENTS

Two new experiments searching for ν_τ appearance in a ν_μ beam have been set up at CERN; CHORUS-WA95 [11] started data taking in May 1994 and NOMAD-WA96 [13] is continuing installation. They both aim at detecting the ν_τ -induced CC reaction $\nu_\tau N \rightarrow \tau^- X$ and several decay modes of the τ . The CHORUS experiment has adopted the emulsion technique to detect the decay topology. In the modern version, events to be measured in the emulsion are selected kinematically for the missing transverse momentum feature characteristic for τ decay. The particle tracks associated with these selected events are measured with scintillating fiber techniques. The detector,

Figure 4. Emulsion target and fiber trackers of the CHORUS experiment [11].

calorimeter for measuring the hadron shower direction and energy and a muon spectrometer (figure 5). The microscopes for emulsion measurements are computer-assisted and scan along the tracks of selected events measured by the scintillating fiber trackers (see figure 4). Using this technique a total efficiency of $\sim 5\%$ for detecting one of the τ -decay modes can be achieved (table 1). If the ν_μ - ν_τ oscillation phenomenon should exist at the level of the present 90% C.L. they would observe 64 events (table 1) of reaction (3) and a background of ~ 1.7 events. If some candidates will be detected their method provides for additional discrimination between reaction (3) and background due to charm particle production by the small $\bar{\nu}_\mu$ and $\bar{\nu}_e$ components of the beam and due to elastic pion scattering without visible

Figure 5. The CHORUS detector [11].

Table 1
Efficiency of τ^- detection

Experiment	τ^- Decay mode	Branching ratio (BR)	Efficiency (ϵ)	N_τ *	Background	Background after vertex cut
CHORUS	$\mu^- \bar{\nu}_\mu \nu_\tau$	0.178	0.098	23	0.27	
	$h^-(\pi\pi^0)\nu_\tau$	0.50	0.046	29	0.72	
	$\pi^-\pi^+\pi^-(\pi\pi^0)\nu_\tau$	0.13	0.065	12	0.71	
	ϵ total = BR $\cdot$ ϵ		0.0494	64	1.70	0.4
NOMAD	$\nu_\tau e^- \bar{\nu}_e$	0.178	0.135	39	4.6	
	$\nu_\tau \mu^- \bar{\nu}_\mu$	0.178	0.039	11	2.2	
	$\nu_\tau \pi^-\pi^+\pi^-\pi\pi^0$	0.138	0.077	18	< 0.2	
	$\nu_\tau \pi^-$	0.11	0.014	3	< 0.2	
	$\nu_\tau \rho^-$	0.23	0.020	7	< 0.2	
	ϵ total		0.0477	78	6.8	6.8

* The number of events corresponds to $\sin^2 2\theta = 5 \cdot 10^{-3}$ and $\Delta m^2 \geq 40 \text{ eV}^2$ and a run of $2.4 \cdot 10^{19}$ protons on target.

recoil (white kink). The τ candidate track before the decay kink must balance the p_T of tracks from the hadron vertex. This is generally not the case for background events. Requiring that vertex configuration in addition reduces the background to 0.4 events and the acceptance efficiency to 4.5%. If no event or one event were observed this would correspond to a 90% C.L. of $\sin^2 2\theta_{\mu\tau} > 2.7 \cdot 10^{-4}$ at $\Delta m^2 \sim 50 \text{ eV}^2$. If some events were observed the discovery potential could be significantly enhanced by using the vertex condition; e.g. for the observation of events corresponding to $\sin^2 2\theta_{\mu\tau} \sim 5 \cdot 10^{-4}$ the statistical significance can be increased by a factor of about 30. The NOMAD-WA96 experiment [6] relies entirely on kinematical selection of events. Special emphasis is put on the detection of the decay $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\mu$. As the flux of ν_e is only $\sim 1\%$ compared to that of ν_μ the background is potentially lower. Events

due to reaction (3) are expected not to have a 180° transverse correlation between the charged lepton from τ decay and the hadron shower direction. The azimuthal correlation between the missing p_T vector (ν_τ from τ decay in reaction (3)) and the hadron shower favours large angles. Estimates of the acceptance efficiency, the number of events detected if $\sin^2 2\theta_{\mu\tau} = 5 \cdot 10^{-3}$ and the background are given in table 1 as well. Because of the larger background, ν_τ induced, events observed in this experiment will have smaller statistical significance than in the CHORUS experiment. However, the information is available in real time, whereas for CHORUS additional time for emulsion handling and scanning is required. The set-up of the NOMAD experiment is shown in figure 6. It is using the magnet of the UA1

Figure 6. Set-up of the NOMAD experiment [13].

experiment for measuring charged particle momenta. Electrons are identified by transition radiation. A calorimeter measures the direction and energy of the photon final state. Muons are identified by transmission through an iron absorber. Depending on the outcome, I can anticipate two scenarios :

(1) Some events are found corresponding to $\sin^2 2\theta_{\mu\tau} > 5 \cdot 10^{-4}$, $\Delta m^2 > 50 \text{eV}^2$. Then a new experiment will be required which can determine whether the mass of ν_τ is of cosmological relevance, i.e. $m_{\nu_\tau} \sim 10 \text{eV}$. Such an experiment needs a factor ~ 20 smaller value of L/E (see eq (1)). This condition can be realized e.g. at the CERN LHC by moving

closer to the source and using higher neutrino energy. Because of the higher proton energy (7TeV) the prompt ν_τ background is large and adds to the difficulty of the experiment.

(2) No events above background are found. A new experiment in the CERN WBB with a sensitivity of $\sin^2 2\theta_{\mu\tau} \sim 10^{-5}$ would then be interesting. Neither CHORUS nor NOMAD can reach this and a new approach to the detection of the decay topology with a 50 times more massive target is then required. A detector based on the principle of the TPC in cryogenic materials, [16] using CH_4 , may achieve this sensitivity.

5. FUTURE PROSPECTS

Apart from pursuing the appearance of ν_τ with a mass of cosmological relevance it is also interesting to search for smaller neutrino masses. Experimental studies of atmospheric neutrinos may indicate the possibility of oscillation $\nu_\mu - \nu_\tau$ or $\nu_\mu - \nu_e$ with $\Delta m^2 \sim 10^{-3} \text{eV}^2$ and $\sin^2 2\theta \sim 1$. Here a disappearance experiment or an experiment with two detectors combining both disappearance and appearance techniques may be of interest. Several such experiments have been worked out or have been proposed.

In Europe there is the ICARUS experiment with one to three 5K tons targets in the Gran Sasso Laboratory using a ν_μ beam from CERN.

This experiment is now under study. It would be able to explore domains of $\Delta m_{e\mu}^2$ down to 10^{-4}eV^2 and of $\Delta m_{\mu\tau}^2$ down to 10^{-3}eV^2 . The use of an accelerator neutrino beam has obvious advantages over experiments using atmospheric neutrinos as the beam has a well-known neutrino energy spectrum, composition, direction and timing.

6. SUMMARY

New accelerator based searches of neutrino oscillation can explore the possibility that the ν_τ is the cosmological dark matter candidate. Long baseline experiments are sensitive to another window with $\Delta m^2 \sim 10^{-4} - 10^{-3} \text{eV}^2$. We are looking forward to their results with a sense of excitement because of the tremendous implications.

REFERENCES

1. R. Davis, Prog.Part.Nucl.Phys. 32(1994), in press
K. Nakamura et al., Kamiokande Collaboration, Nucl.Phys. B31(1993)105
P. Anselmann et al., Gallex Collaboration, Phys.Lett. B327(1994)377
J.N. Abdurashitov et al., SAGE Collaboration, Phys.Lett. B328(1994)234
2. Ya. B. Zel'dovich, I.D. Novikov,
Relativistic Astrophysics, Nauka (Moscow)1967
T. de Graaf, Lett.Nuovo Cim.2(1971)979
H. Harari, Phys.Lett. B216(1989)413
3. J. Lefrançois, Rapporteur talk "Precision tests of the Standard Model"
EPS-HEP Conference, Marseille (1993)
4. R. Abela et al., Phys.Lett. B105(1981)263
5. T. Yamazaki et al., Proc. Neutrino 84, World Scientific, Singapore 1984, p.183
6. A.M. Cooper-Sarkar et al., BEBC Collaboration, Phys.Lett. B160(1985)207
7. M.Z. Akrawy et al., OPAL Collaboration, Phys.Lett. B247(1990)448
8. J. Dorenbosch et al., CHARM Collaboration, Phys.Lett. B166(1986)473
9. S.R. Mishra et al., CCFR Collaboration, Phys.Rev.Lett. 59(1987)1397
10. P. Vilain et al., CHARM II Collaboration, Phys.Lett. (to be published)
S. Petrak, Diploma thesis, Freie Universität Berlin, 1994 (unpublished)
11. M. de Jong et al., CHORUS Collaboration, CERN-PPE/93-131 (July 20, 1993)
12. C. Albright and E. Shrock, Phys.Lett. B84(1979)123
13. L. DiLella, Proc. Neutrino 92, Nucl.Phys.B 31(1993)319
14. M. Gruwé et al., CHARM II Collaboration, Phys.Lett. B309(1993)463
15. C.Y. Pang et al., Phys.Rev. D8(1973)1989
16. C. Rubbia, Internal report CERN - PPE/93-08
17. N. Ushida et al., E531 Collaboration, Phys.Rev.Lett. 57(1986)2897
18. C. Haber et al., CCFR Collaboration, Phys.Rev.Lett. 52(1984)1384
19. see J. Schneps, Neutrino 92, Nucl.Phys. B31(1993)307