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Neutrino Oscillation at Accelerators

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Neutrino oscillation at accelerators

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From measurements of the width and of the peak value of the Z^0 pole in e^+e^- annihilations the existence of three neutrino families in nature has recently been derived. Do these families mix or are they distinct? We do not know if the mixing phenomenon exists in nature. Two different types of experiments have been conducted at high energy accelerators in searching for the resulting neutrino oscillation, the apparent disappearance of neutrinos of one flavour as they are propagating and the appearance of neutrinos of a new flavour. Present limits, a new result, advantages and weaknesses of the two approaches and future prospects will be presented and discussed.

1. Introduction

From measurements of the width and of the peak value of the cross section of e^+e^- annihilation to all visible final states at the Z^0 pole we know that there exist three families of light neutrinos in nature. Two of them have been detected by their capture on nucleons, the electron- and the muon-neutrino (ν_e, ν_μ); the third, tau-neutrino (ν_τ), has remained undetected. Do these neutrinos have non-zero mass? Do these families mix or are they distinct? Non-zero neutrino mass is a necessary condition for neutrino mixing. These questions belong to the most fundamental ones for experimental particle physics. Answers may come from searches for neutrino oscillation. The mixing of neutrino families can be described by a matrix, similar to the Cabibbo–Kobayashi–Maskawa quark mixing matrix. Assuming neutrino masses are generated by a see-saw mechanism, oscillation will be dominantly a phenomenon between the families of the two heaviest leptons, the muon and the tau. The frequency of the oscillation term is given by the difference of the neutrino masses squared. The probability of appearance of neutrinos of a new flavour, ν_b in a beam of ν_a or disappearance of ν_a is given by the well-known expression,

$$P_{ab} = \sin^2 2\theta_{ab} \sin^2(1.27(L/E)\,\Delta m^2_{ab}), \tag{1}$$

where L is the distance to the neutrino source in km and E the neutrino energy in GeV. Results from recent experiments on solar neutrinos, which are reported elsewhere at this meeting, are consistent with a Mikheyer–Smirnov–Wolfenstein solution to the solar neutrino problem (Fiorini 1992; Nakamura 1993; Anosov *et al.* 1993; Anselmann *et al.* 1993). One of the favoured solutions gives a mass to the ν_τ which would make it a candidate for dark matter ($m_{\nu_\tau} \approx 20$ eV) (Harari 1989). Also recent experimental results on the unisotropy of the cosmic background radiation favour ν_τ with $m_{\nu_\tau} \approx 7$ eV. Search for neutrino oscillation is straight forward at high energy accelerators. They are sources of collimated $\nu_\mu(\bar{\nu}_\mu)$ beams of high intensity. Their energy and the distance to the source are well-known and matched to detect

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oscillation for $m_{\nu_\tau} > 1$ eV. Questions about the relative abundance of ν_μ and ν_e were asked in the first neutrino experiment at CERN which confirmed the discovery of the muon-neutrino. It also detected a small component of electron-neutrinos. What was their origin? Were they produced by neutrino oscillation? Their abundance agreed with K_{e3} decays of kaons.

2. Experimental methods

Two methods have been used for this search. One consists in searching for the appearance of a neutrino of another family (ν_b) difference from the dominant component (ν_a) of the beam, e.g. ν_τ or ν_e. The other method consists of searching for the corresponding disappearance of ν_a. The relation of the two methods is given by unitarity

$$P_{aa} = 1 - P_{ab}. \tag{2}$$

Both methods have distinct advantages and disadvantages.

(a) *Disappearance experiments*

The disappearance search is inclusive; ν_a may disappear to any kind of neutrino. The sensitivity to different values of the Δm^2 can be extended to smaller values by increasing the distance of the detector to the source. The number of events N induced by ν_a in this FAR detector can be firmly predicted by measuring simultaneously their number in a NEAR detector, provided the beam can be accurately described as coming from a point source. In this case

$$R = \frac{\mathrm{N(FAR)}}{\mathrm{N(NEAR)}} = \frac{M(\mathrm{FAR})/S(\mathrm{FAR})}{M(\mathrm{NEAR})/S(\mathrm{NEAR})}\left(\frac{L(\mathrm{NEAR})}{L(\mathrm{FAR})}\right)^2, \tag{3}$$

where M stands for the effective target mass, S for the surface area and L for the distance to the source. Deviations from this simple relation occur if the acceptance for the NEAR detector exceeds the maximum value of $p_T \approx 30$ MeV from pion decay, because the relative acceptance for neutrinos from pion and $K_{\mu3}$ decays is different, and if the geometry of the decay region is not symmetric. All these deviations can be calculated. A measurement at a third distance can be used to check the calculations. The first measurements with two detectors have been performed at CERN by the CDHS (Dydak *et al.* 1989) and the CHARM (Bergsma *et al.* 1984) Collaborations. Another source of uncertainty occurs in the process of identification of interactions of ν_a. At high energy accelerators beams of ν_μ are used and the charged current reaction (CC)

$$\nu_\mu \mathrm{N} \rightarrow \mu^- \mathrm{X} \tag{4}$$

is recorded. The efficiency for detecting this reaction depends on the neutrino energy because of detection thresholds for E_X and E_μ. The mean energy, however, varies with the distance to the detector because of the decay kinematics. Therefore, the efficiencies of the FAR and NEAR detectors do not cancel completely as suggested in (3). The same caution must be taken for the fraction of neutral current (NC) events $\nu_\mu \mathrm{N} \rightarrow \nu_\mu \mathrm{X}$ which are misidentified as candidates for the CC reaction (4). This fraction is, in general, different for the NEAR and the FAR detector.

The sensitivity for establishing a statistically significant deviation of P_{aa} from 1 (equation (2)) to detect a term due to $P_{ab} \neq 0$ depends on the event rates in the two

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detectors and on the remaining uncertainties on deviations from (3). I shall come back to some quantitative remarks in connection with my discussion of future projects.

(*b*) *Appearance experiments*

The search for appearance of $\nu_b \neq \nu_a$ in a beam can be performed at a single distance. The ratio L/E gives the limit of sensitivity for Δm^2_{ab}. The limit on $\sin^2 2\theta_{ab}$ which can be reached depends on the event rate, to some extent also on the neutrino energy because of the threshold for the reaction $\nu_\tau N \rightarrow \tau^- X$ and on the backgrounds both of prompt ν_b present in the beam and of other misidentified reactions. For ν_e this prompt background is about 1%; the prompt ν_τ background depends strongly on the proton energy of the accelerator because of the energy dependence of the cross section of the reaction $pN \rightarrow D_s X$, $D_s \rightarrow \nu_\tau \tau$. At the CERN 450 GeV SPS the flux ratio $\varphi(\nu_\tau)/\varphi(\nu_\mu) \approx 10^{-7}$ is very favourable for a search for ν_τ appearance. The dominant limitation is due to, both the event rate (target mass), and to background. Search for ν_μ–ν_τ oscillation consists in detecting the ν_τ induced reaction

$$\nu_\tau N \rightarrow \tau^- X. \tag{5}$$

There are several experimental ways to do this. The most direct way is the observation of the τ decay topology. The transverse decay length is *ca.* 90 μm and the longitudinal *ca.* 250 μm.

Detection of the decay kink for the dominant decay modes into one charged particle (86%) or of a 'star' in the case of $\tau \rightarrow \pi^-\pi^+\pi^-(n\pi^0)\nu_\tau$ (14%) requires a special detector with spacial resolution of better than 10 μm. Only the emulsion technique gives the required resolution. Another approach is to select events with missing transverse momentum in correlation with the hadron shower direction (Albright *et al.* 1979). This approach, which was not very successful in the search for charm particle production will also be tried.

A third approach is an interesting extension of the disappearance and appearance methods (Winter 1988, 1990). In about 82% of all decays the τ lepton does not produce a muon. Appearance of ν_τ therefore reduces the number of events with a muon and increases the number of events without a muon. A measurement of the ratio of muonless events (NC) and of events with a muon (CC) is therefore sensitive to ν_τ appearance. Performing another measurement of this ratio in a NEAR detector one can form a double ratio

$$R = \frac{(\mathrm{NC}/\mathrm{CC})\,\mathrm{FAR}}{(\mathrm{NC}/\mathrm{CC})\,\mathrm{NEAR}}, \tag{6}$$

which is less sensitive to deviations of the beam from a point source and from differences in the mean energies in the two detectors. Several such measurements are presently under consideration; I will describe them in §4.

The search for appearance of ν_e in a ν_μ beam is subject to difficulties from a prompt background of *ca.* 1% which has to be subtracted and from electron/photon discrimination. The background of ν_e can be measured in a near detector; a double ratio,

$$R = \frac{(\mathrm{N(e)}/\mathrm{CC}(\mu))\,\mathrm{FAR}}{(\mathrm{N(e)}/\mathrm{CC}(\mu))\,\mathrm{NEAR}}, \tag{7}$$

therefore can largely eliminate the prompt background problem. The result can also be interpreted as a limit on ν_τ appearance, because of the *ca.* 17% branching ratio

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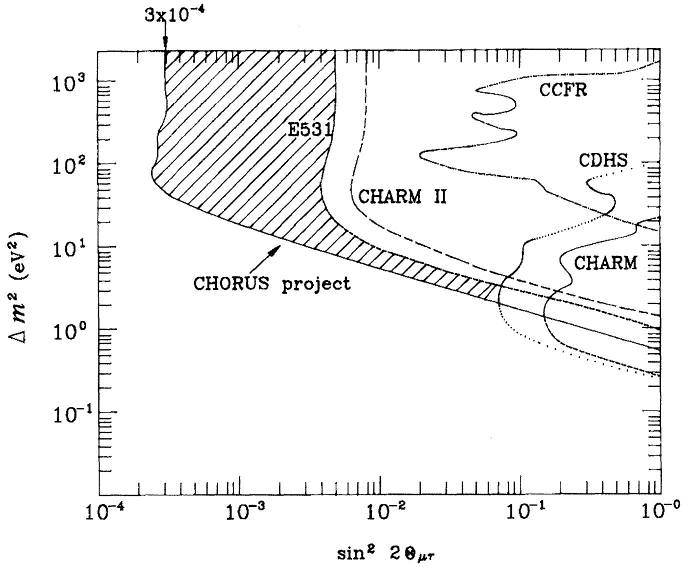

Figure 1. Exclusion plot (90 % CL) for ν_μ–ν_τ oscillation showing results from E531 (Ushida *et al.* 1986), CHARM II (Gruwé *et al.* 1993), CCFR (Habes *et al.* 1984), CDHS and CHARM (Schneps 1993) and the new area which can be explored by the CHORUS (Armenise *et al.* 1993) and NOMAD (DiLella 1993) experiments.

of $\tau \rightarrow e\nu_e\,\nu_\tau$. In all experiments with two detectors a region of sensitivity for Δm^2 is selected; the lower limit is defined by the FAR detector and the upper limit by the close detector. The upper limit on Δm^2 is not shown in table 2 and on figure 11. Appearance experiments, in contrast, are sensitive to oscillation with $\Delta m^2 \geqslant (E/L)$ const.

3. Review of results

No compelling evidence for oscillation has been reported from accelerator experiments. There is one new negative result on ν_μ–ν_τ oscillation reported very recently by the CHARM II Collaboration which is approaching in sensitivity the old limit of Ushida *et al.* (1986) obtained with an emulsion-hybrid detector (see figure 1) at Fermilab (E531). The CHARM II Collaboration (Gruwé *et al.* 1993) used a completely different technique. They selected quasi-elastic ν_τ interactions followed by the decay $\tau \rightarrow \pi\nu_\tau$. These events appear in the fine-grain calorimeter of the CHARM II detector as a single track followed by a hadronic shower (see figure 2). Background comes from NC reactions with a single charged pion. Requiring a minimum track length of 15 planes of the detector corresponding to *ca.* 1.7 interaction lengths and a shower energy greater than 10 GeV they found 124 events, 77 in the ν_μ beam and 47 in the $\bar{\nu}_\mu$ beam. Fitting the kinematical distribution of these events in transverse energy and in the shower energy (figure 3) to a simulation of the ν_τ reaction and of the background reaction they derived at the 90 % exclusion region shown in figure 1. The maximum sensitivity is reached for $\Delta m^2 = 50$ eV^2 where they exclude values of $\sin^2\theta_{\mu\tau} > 6.4 \times 10^{-3}$. Results of the Fermilab experiment E531 (Ushida *et al.* 1986), and of searches using the disappearance method of ν_τ performed by the CDHS and CHARM Collaborations, as well as those performed by the CCFR Collaboration at Fermilab (Habes *et al.* 1984), are also displayed in figure 1. The

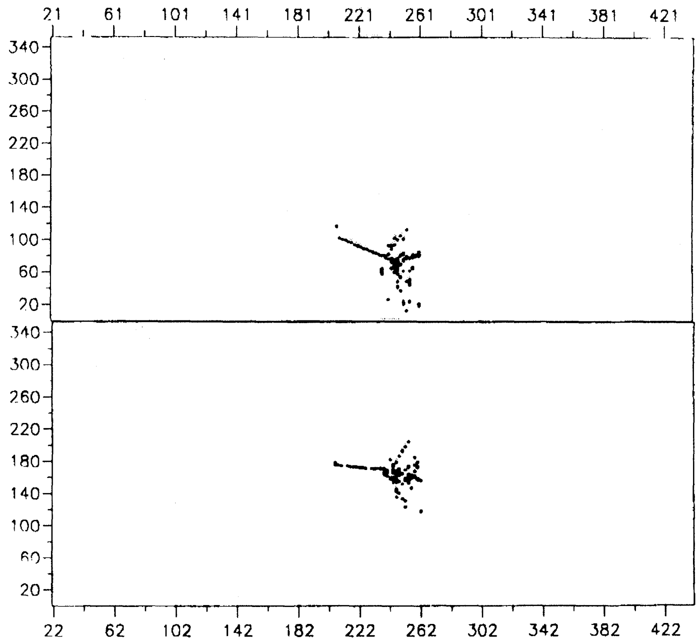

Figure 2. Candidate event of the quasi-elastic $\nu_\tau N \to (\tau^- \to \pi^- \nu_\tau) N'$ reaction observed by the CHARM II Collaboration (Gruwé *et al.* 1993).

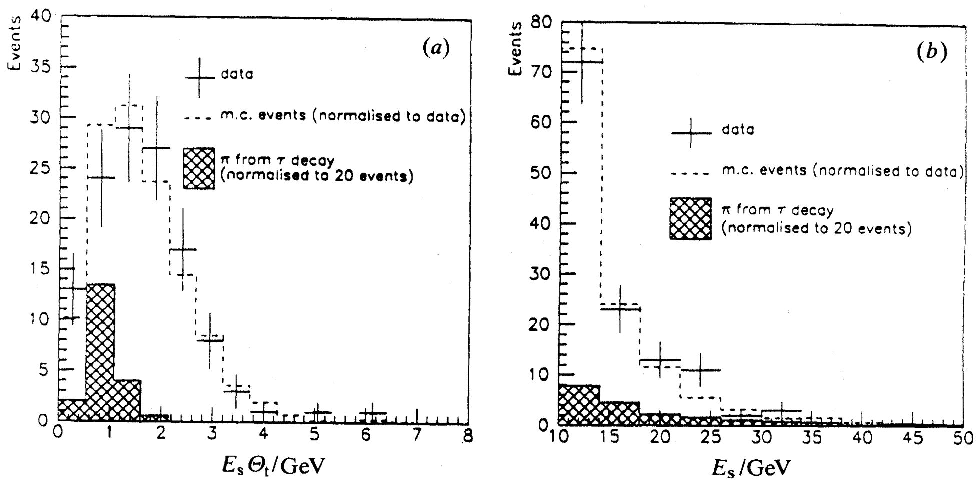

Figure 3. Distribution of (*a*) $E_s\,\theta_t$ and (*b*) E_s for candidates of reaction $\nu_\tau N \to (\tau \to \pi\nu_\tau) N'$, CHARM II Collaboration (Gruwé *et al.* 1993) and MC simulation of background.

estimated sensitivity of new experiments under preparation at CERN (see §4) is shown as well for comparison. In conclusion, the excluded region does not yet eliminate the possibility that the dark matter of the universe is formed by ν_τ. The mixing parameter limit should be further reduced, below the value corresponding to the mixing of the second and third quark family with $\sin^2 2\theta \approx 10^{-3}$. Much less is known about ν_e–ν_τ mixing. The good news is that we are liberated from the 17 keV ghost with a 1 % mixing. The other information in this sector is summarized in figure 4. Assuming again the see-saw mechanism for creating neutrinos masses and that

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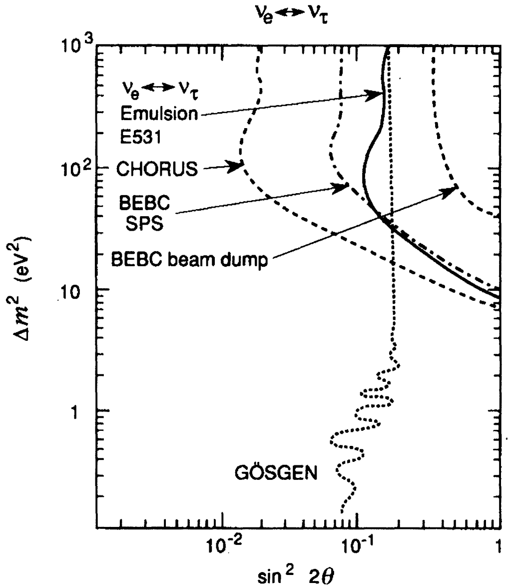

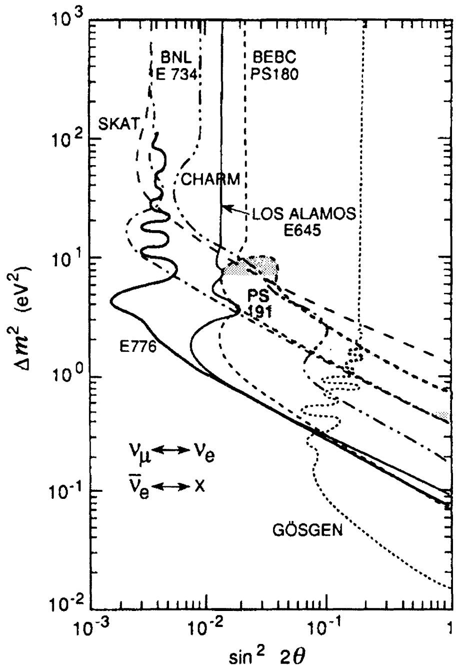

Figure 4. Exclusion plot (90% CL) for ν_e–ν_τ oscillation showing results from E531 (Ushida *et al.* 1986), BEBC SPS (Angelini *et al.* 1986) and BEBC Beam Dump (Schneps 1993) and the sensitivity of CHORUS.

Figure 5. Exclusion plot (90% CL) for ν_μ–ν_e oscillation showing results from previous experiments (Schneps 1993) and more recent ones from Los Alamos (Borodovsky *et al.* 1992), E776 (Ahrens *et al.* 1985), and CHARM (Bergsma *et al.* 1988). The shaded area, reported (Bernardi *et al.* 1986) as positive evidence is excluded by several experiments.

mixing is proportional to the mass difference we must conclude that these experiments are very far away from detecting an effect.

No new results on ν_μ–ν_e oscillation searches have been reported since the last Neutrino Conference in 1992 (Schneps 1993). Figure 5 shows a compilation of the present status. The positive effect in PS 191 (Bernardi *et al.* 1986) can now be safely eliminated as it is not confirmed by BEBC (Angelini *et al.* 1986), CHARM (Bergsma *et al.* 1988), Los Alamos (Borodovsky *et al.* 1992) and E776 at BNL (Ahreus *et al.* 1985).

4. New experiments

Two new experiments searching for ν_τ appearance in a ν_μ beam are presently under preparation at CERN, CHORUS-WA95 (Armenise *et al.* 1993) and NOMAD-WA96 (DiLella 1993). They both aim at detecting the ν_τ induced CC reaction

$$\nu_\tau \mathrm{N} \rightarrow \tau^- \mathrm{X} \tag{8}$$

and several decay modes of the τ. The CHORUS experiment has adopted the emulsion technique to detect the decay topology. In the modern version adopted, 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 fibre techniques. The detector, therefore, consists of an emulsion target and a tracker part (figure 6)

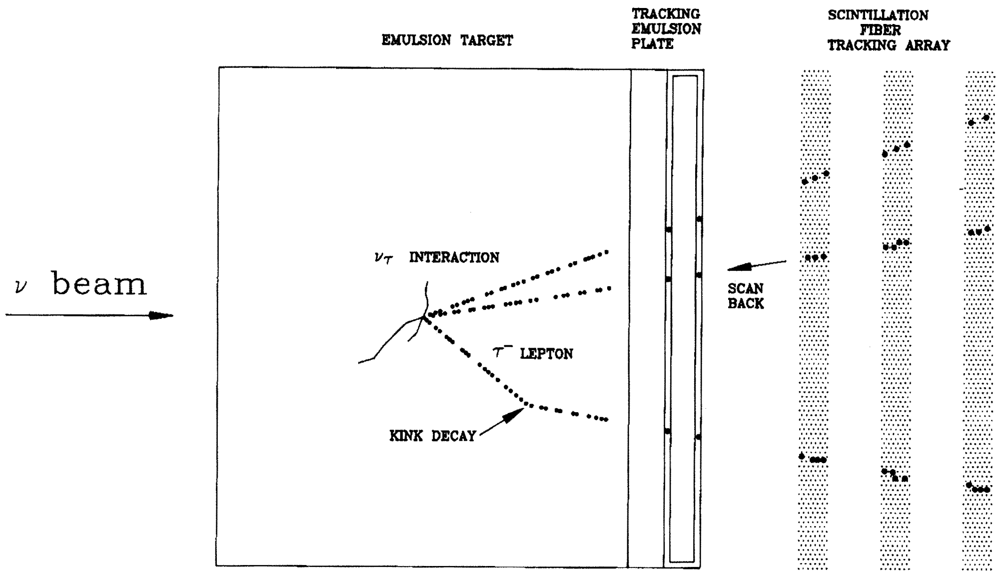

Figure 6. Emulsion target and fibre trackers of the CHORUS experiment (Armenise *et al.* 1993).

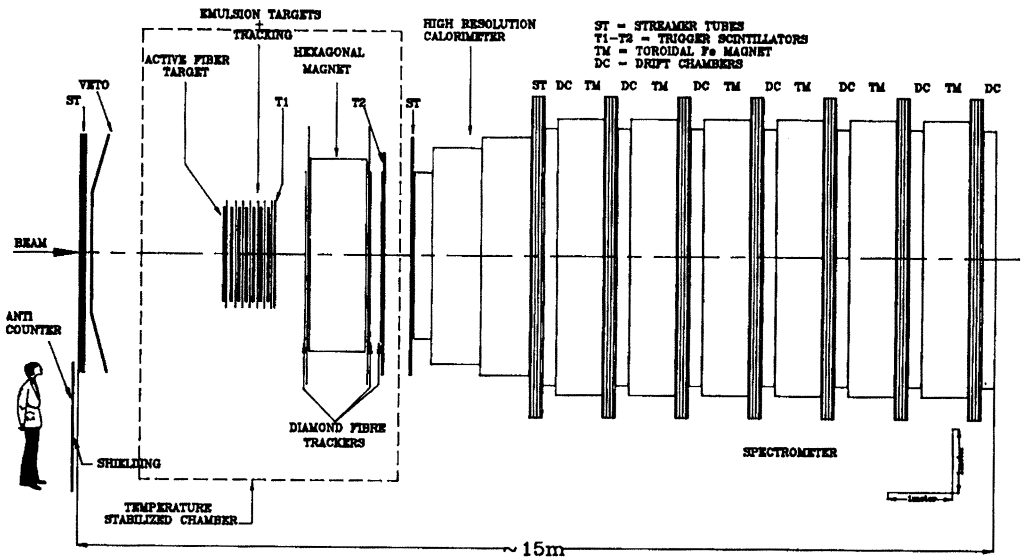

Figure 7. Detector of the CHORUS experiment searching for ν_μ–ν_τ oscillation (Armenise *et al.* 1993).

and of a magnet for measuring particle momenta followed by a calorimeter for measuring the hadron shower direction and energy and a muon spectrometer (figure 7). The microscopes for emulsion measurements are computer-assisted and measure along the tracks of selected events measured by the scintillating fibre trackers (see figure 6). Using this technique a total efficiency of about 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% CL they would observe 64 events (table 1) of reaction (6) and a background of about 1.7 events. If some candidates will be

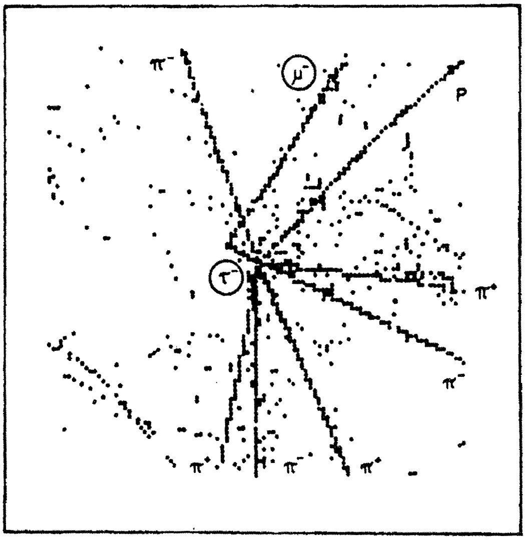

Figure 8. Simulated event $\nu_\tau N \rightarrow (\tau \rightarrow \mu\nu_\mu\nu_\tau)X$ in plane perpendicular to incident neutrino beam (Winter 1990*b*) showing p_T balancing between the tau track and the hadron tracks.

Table 1. *Efficiency of* τ^- *detection*

experiment	τ^- decay mode	branching ratio (BR)	efficiency (ϵ)	N_τ[a]	background	background after vertex cut
CHORUS	$\mu^-\bar{\nu}_\mu\nu_\tau$	0.178	0.098	23	0.27	
	$h^-(n\pi^0)\nu_\tau$	0.50	0.046	29	0.72	
	$\pi^-\pi^+\pi^-(n\pi^0)\nu_\tau$	0.138	0.065	12	0.71	
	ϵ total = BR × ϵ	—	0.0494	64	1.70	0.4
NOMAD	$\nu_\tau e^-\bar{\nu}_\mu$	0.178	0.135	39	4.6	
	$\nu_\tau\mu^-\theta\bar{\nu}_\mu$	0.178	0.039	11	2.2	
	$\nu_\tau\pi^-\pi^-\pi^+ + n\pi^0$	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

[a] The number of events corresponds to $\sin^2 2\theta = 5\times10^{-3}$ and $\Delta m^2 \geqslant 40\ \mathrm{eV}^2$ and a run of 2.4×10^{19} protons on target.

detected their method provides for additional discrimination between reaction (6) 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 recoil (white kink). The τ candidate track before the decay kink must balance the p_T of tracks from the hadron vertex (see figure 8, simulated candidate). 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% CL of $\sin^2 2\theta_{\mu\tau} > 2.7\times10^{-4}$ at $\Delta m^2 \approx 50\ \mathrm{eV}^2$. 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 $\sin^2 2\theta_{\mu\tau} \approx 5\times10^{-4}$ the statistical significance can be increased by a factor of about 30 (see figure 9).

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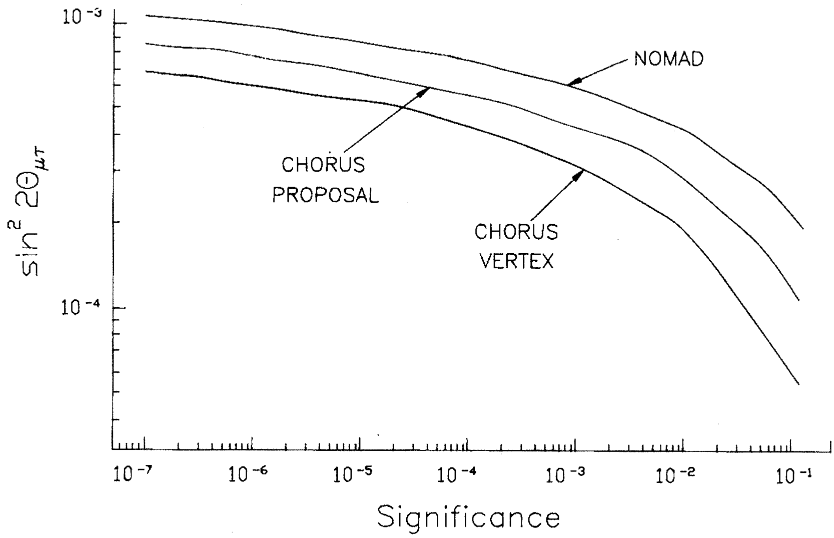

Figure 9. Statistical significance of ν_μ–ν_τ oscillation events as a function of $\sin^2 2\theta_{\mu\tau}$ for the NOMAD experiment (DiLella 1993), the CHORUS experiment, and CHORUS with the requirement of p_T balance at the vertex (Armenise *et al.* 1993).

The NOMAD-WA96 experiment (DiLella 1993) relies entirely on kinematical selection of events. Events due to reaction (6) are expected not to have a 180° 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 (6)) and the hadron shower favours large angles. Estimates of the acceptance efficiency, the number of events detected if $\sin^2 2\theta_{\mu\tau} = 5\times 10^{-3}$ 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. In the example given before for $\sin^2 2\theta_{\mu\tau} = 5\times 10^{-4}$ (see figure 9) the CHORUS experiment will have a statistical significance which is a factor of 100 superior to the NOMAD experiment. The set-up of the NOMAD experiment is shown in figure 10. It is using the magnet of the UA1 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.

Both experiments are planning data-taking runs from April 1994.

Depending on the outcome, I can anticipate two scenarios:

1. Some events are found corresponding to $\sin^2 2\theta_{\mu\tau} > 5\times 10^{-4}$, $\Delta m^2 > 50\ \mathrm{eV}^2$. Then a new experiment will be required which can determine whether the mass of ν_τ is of cosmological relevance, i.e. $m_{\nu_\tau} \approx 20$ eV. Such an experiment needs a factor of about 20 smaller value of L/E (see equation (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 (7 TeV) 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 $\sin^2 2\theta_{\mu\tau} \approx 10^{-5}$ 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

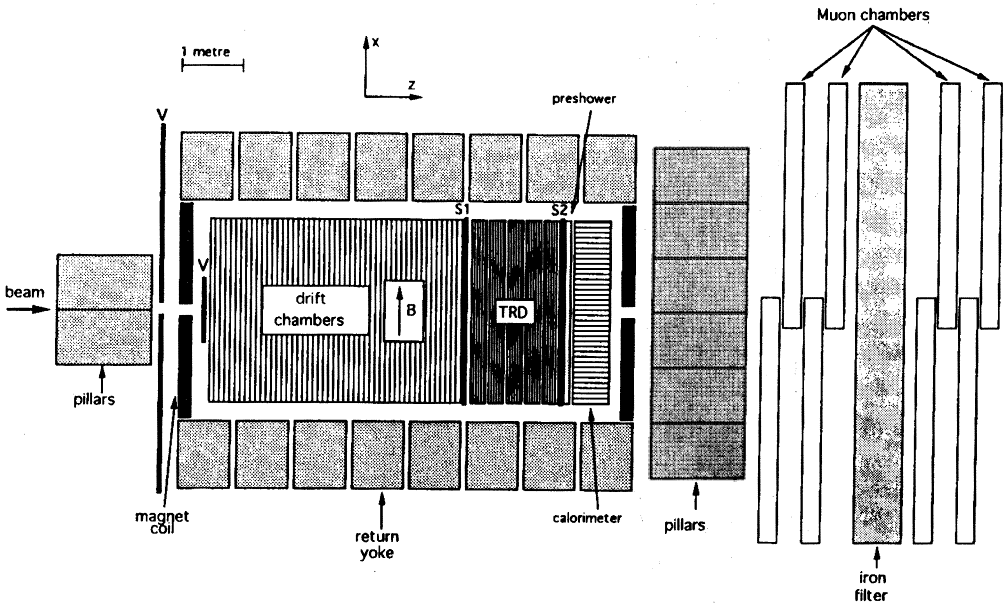

Figure 10. Experimental set-up of the NOMAD experiment (DiLella 1993).

Table 2. *Long baseline neutrino oscillation projects*

detector	distance/km	mass/kt	$\Delta m^2_{\mu e}$ [a]	$\Delta m^2_{\mu\tau}$ [a]
ICARUS (TPC)	731	5	2×10^{-4}	2×10^{-3}
SUPERKAMIOKANDE (water)	8752	20	5×10^{-5}	—
SOUDAN 2 (calorim.) (P822)	730	1+5	10^{-3}	2×10^{-3}
BNL 889 (water)	20	6	—	5×10^{-3}

[a] Limit for $\sin^2 2\theta = 1$.

is then required. A detector based on the principle of the TPC in cryogenic materials (ICARUS (Rubbia 1993)), using CH_4, may achieve this sensitivity.

5. Future prospects

Apart from persuing 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 seem to indicate the possibility of oscillation ν_μ–ν_τ or ν_μ–ν_e with $\Delta m^2 \approx 10^{-3}\,\text{eV}^2$ and $\sin^2 2\theta \approx 0.1$. 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. They are summarized in table 2. None of them has made a detailed study of systematic uncertainties.

In Europe there is the ICARUS experiment with one to three 5 K tons targets in the Gran Sasso Laboratory using a ν_μ beam from CERN and the Superkamiokande experiment with a 20 K tons target with a ν_μ beam from CERN. The relative merits depend on the possibilities of identification of some classes of events and on the event rate. The distance determines the lower limit of Δm^2 which can be detected. In the

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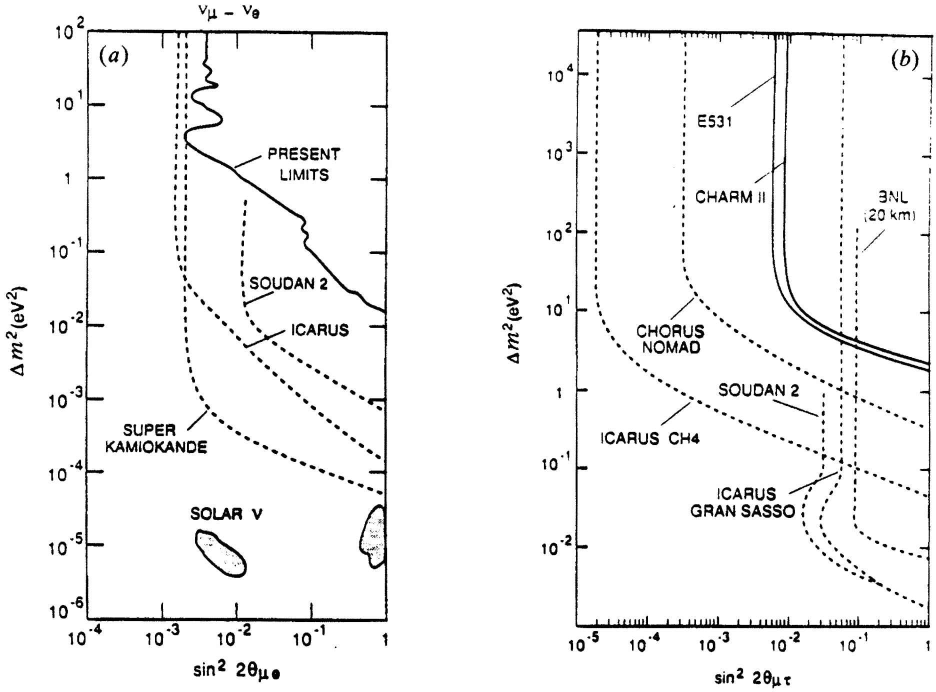

Figure 11. Limits of sensitivity of future projects for oscillation searches, (*a*) ν_μ–ν_e, (*b*) ν_μ–ν_τ. Limitations of the sensitivity to Δm^2 because of the NEAR detector measurements are not shown.

U.S. there are also two projects: the Soudan 2 detector in a ν_μ beam from Fermilab and an experiment at BNL using three detectors over 20 km distance. A comparison of the sensitivities is shown in figure 11*a*, *b*. Having spelt out the difficulties of these experiments in §2*b* let me also add their advantages over experiments with atmospheric neutrinos. The spectrum of E_ν is well known, the beams have known direction and timing, facilitating the rejection of background, and they give high event rate. One can alternate between runs with ν_μ and $\bar{\nu}_\mu$ beams and search for matter induced effects which will introduce an asymmetry in the associated event rates. Such matter effects between CERN and Gran Sasso from a comparison of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation have been studied by Fiorentini & Ricci (1993).

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 $\Delta m^2 \approx 10^{-4}$–$10^{-3}$ eV^2. We are looking forward to their results with a sense of excitement because of the tremendous implications.

In preparing this paper I have enjoyed discussions with several people, among them H. Harari, L. Okun, D. Perkins, C. Rubbia and Y. Totsuka.

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