Oscillations with Laboratory Neutrinos *

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The status of searches for oscillations using neutrinos produced in the laboratory is reviewed. The most recent results from experiments approaching completion are reported and the potential capabilities of long baseline projects being developed in USA and Europe are considered and compared. The steps that should naturally follow this new generation of experiments are outlined and the impact of future facilities - such as neutrino factories or conventional superbeams - in precision measurements of elements of the neutrino mixing matrix is discussed.

1. Introduction

In recent years the existence of neutrino oscillations has become a commonly accepted fact. The evidence rests upon the convincing results obtained by a number of well known experiments on atmospheric and solar neutrinos, most notably among them SuperKamiokande and Gallex [1,2]. However some ambiguity still remains on which neutrino flavours are involved in the transitions, including a possible sterile ν. Also the values of parameters that characterise the oscillations have to be more accurately determined.

The overall situation does not become clearer when experiments performed so far at accelerators and reactors are considered as well. All have in fact shown no evidence for neutrino mixing and have set only upper limits on the oscillation parameters. All, with the exception of LSND [3,4]! In this experiment, oscillations $\nu_\mu \to \nu_e$ are observed with a probability of about 0.3%. This claim can not be lightly dismissed, since, if correct, it would have implications on the interpretation of the solar and atmospheric neutrino data, perhaps making it necessary to invoke the existence of a sterile neutrino to obtain a consistent description of all available data.

Irrespective of the findings of that particular experiment, it is true that the next generation of experiments at accelerators and reactors is going to play a major role in the field of neutrino oscillations. Not only could the LSND claim be verified or disproved but also - for the first time - the region of mixing parameters suggested by the atmospheric and solar neutrino results will be explored in a controlled manner using beams from FNAL and CERN [5,6] and from a number of reactors[7].

The purpose of this report is to give an account, albeit subjective and partial, of the *parallel* session on *Laboratory Neutrinos* at this Workshop, summarising the many interesting contributions, often followed by lively discussions. It is confined to the topics debated in the session and it is organised as follows. In Section 2, the results from current experiments are discussed. Section 3 deals with the capabilities of long baseline projects in USA and Europe. Section 4 reviews the situation on the knowledge of the neutrino mixing matrix to identify the points of particular interest on which future experiments should focus. Some specific issues, such as matter effects and CP violation in the leptonic sector are considered in conjunction with the options for new sources of laboratory neutrinos. Conclusions are drawn in Section 5.

2. Current Experiments

2.1. $\nu_\mu \to \nu_\tau$ Searches

No surprises on the search for $\nu_\mu \to \nu_\tau$ oscillations were reported by CHORUS and NOMAD, the two short baseline experiments that have con-

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cluded data taking in the CERN neutrino Wide Band beam and have almost completed the analyses [8,9].

Both are *appearance* experiments since they aim at detecting the presence of ν_τ in a beam that at production has a very small contamination of such particles. They explore the region of large Δm^2 ($> 50\ eV^2$) and small mixing angles. This region was considered promising - at the time of the proposals (1990) - by some seesaw models in which the heaviest neutrino mass eigenstate would be mostly ν_τ with m_{ν_τ} of order of a few eV, on the basis of a supposed hierarchy in mass scale. A value therefore relevant for cosmology, in a scenario (not favoured any longer) in which neutrinos contribute significantly to the dark matter in the Universe.

In the two experiments the τ lepton, produced in ν_τ charged current interactions (CC), is identified through the "observation" of its decay achieved using different and complementary techniques. These will be only briefly outlined here, while details may be found in [8–11].

In NOMAD, criteria based upon the different energy/momentum sharing and angular correlation between the **observed** lepton and the hadrons are used to discriminate ν_τ from ordinary ν_μ and ν_e CC interactions. Several kinematic variables - describing the behaviour and properties of the **produced** lepton and of the hadronic system - are combined into likelihood functions for *τ-decay candidates* and background events. The search takes place in specific regions of the space defined by these functions. The regions are selected *a priori* - by means of a simulation and **without** looking at the data - as those that maximise the sensitivity of the experiment and constitute the *signal box*. The precise limits depend on the τ decay channel under consideration, since the sources of background contribute differently to different decay modes. All channels with the exclusion of $\tau \rightarrow \mu\ \nu_\tau\ \bar{\nu}_\mu$ decay are included in the analysis with efficiencies ranging between 0.6% and 6% and with the decay $\tau \rightarrow e\nu_\tau\bar{\nu}_e$ having a prominent role, given the excellent electron identification capability of the NOMAD detector. The correctness of the various simulations involved is assured by the observed agreement between data and predictions in control samples, that is sets of data where no τ's are expected to be detected, such as outside the signal box and the sample that would contain the wrong sign (positive) τ leptons. Once the description adopted is deemed satisfactory, one is allowed to *open* the signal box and establish the presence of τ decay candidates.

In the hybrid setup of CHORUS, τ's are identified on an event-by-event basis by requiring that the vertex at which they decay be *visually* observed and the decay topology reconstructed. For this reason and because they provide the spatial resolution necessary to distinguish in space the decay point from the primay ν interaction vertex, nuclear emulsions are employed as target in CHORUS. They are used in a unprecedented quantity ($800kg$), given the need for a large mass, capable of recording the number of neutrino interactions necessary to achieve the goals of the experiment. An approximate localisation of the interaction point within the emulsion target is performed by the electronic detectors, located downstream; this step (prediction) is followed by the emulsion scan, in what may be considered a second stage of data taking. The methods of emulsion scanning have evolved with time (and the speed at which the scan is performed has increased more than one hundred fold over the lifetime of CHORUS); they all aim at the detection of the peculiar decay topology: a sudden change in the direction (**kink**) of a charged particle trajectory observed in the emulsion, at a distance from the interaction vertex compatible with the typical τ decay length. Therefore the decay channels are restricted to $\tau \rightarrow \mu\ \nu_\tau\ \bar{\nu}_\mu$ and $\tau \rightarrow \nu_\tau h^-\ (n\pi^\circ)$ [2] in which either the muon or the hadron can be followed towards the ν-interaction point for kink detection. This is performed by fast hardware processors coupled to microscopes equipped with CCD cameras. However, once a possible decay candidate has been found, more precise, computer-assisted measurements are performed by a trained operator, to accept or rule out a τ decay. The challenge is of course to reduce to

[2] $\tau \rightarrow e^-\nu_\tau\ \bar{\nu}_e$ is excluded because typically it is not possible to select one particle trajectory to follow back in the emulsion when showering electrons are present.

a minimum this human intervention which in itself is a slow procedure, hence the development of different strategies in the various phases of the experiment.

After analyses of a sample of about 144000 1μ and 20000 0μ events in CHORUS and of about 485000 NC events in NOMAD, both experiments find no evidence for oscillations, the observations being consistent with the expected background. A summary of the results from both experiments is given in table 1 (where N_τ^{max} indicates the number of τ expected if the probability of oscillation were equal to 1) and the limits obtained are shown in fig. 1.

Channel	N_τ^{max}	**Bkg.**	**Observed**
CHORUS 1μ	5014	0.1	0
CHORUS 0μ with Φ cut	2004	1.1	0
NOMAD Total	14415	51.1 ± 5.4	52

Table 1
Estimated number of observable ν_τ CC interactions if $P(\nu_\mu \to \nu_\tau) = 1$, in CHORUS and NOMAD. Indicated are the expected backgrounds as well as the observed number of events.

Some comments are appropriate on the way in which the upper limit on the number of ν_τ candidates (and therefore the contours shown in fig. 1) is evaluated. A paper by Feldman and Cousins [12], in which the so called *unified approach* was introduced, generated a considerable amount of work - to the point that entire workshops have been devoted to the subject! - on confidence levels and the best way to combine several null observations to obtain an upper limit, with specific application to neutrino oscillations. Using this method, for large Δm^2, NOMAD finds that $P(\nu_\mu \to \nu_\tau) < 1.7 \cdot 10^{-4}$. CHORUS on the other hand, employing a different statistical approach

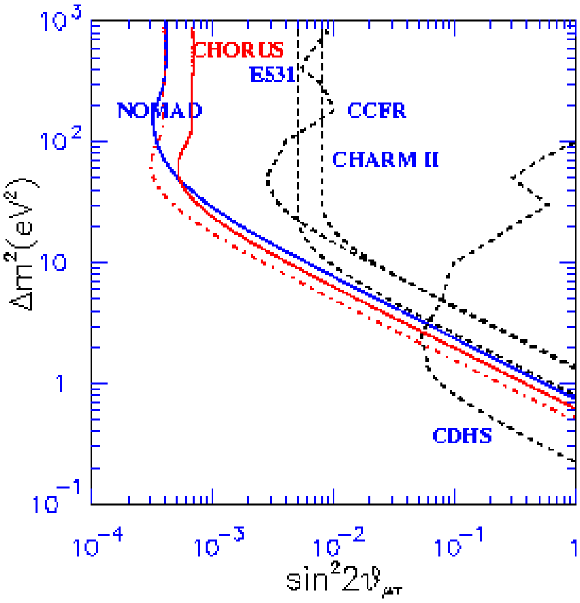

Figure 1. Limits on $\nu_\mu \to \nu_\tau$ mixing from CHORUS and NOMAD. The dashed line almost superimposed to the NOMAD limit for large Δm^2 is the result of an analysis of CHORUS data in the *unified approach* mentioned in the text.

[13], finds a value of $3.4 \cdot 10^{-4}$ that becomes $2 \cdot 10^{-4}$ in the unified approach.

Certainly this is not the venue for a discussion on statistical intricacies, however it is interesting to observe that the results obtained so far are in **all** cases better than the sensitivity. Of this we had at least three examples in our session [9,8,14] and others have been reported in the literature. This in spite of the fact that the sensitivity is "defined as the **average** upper limit that it would be obtained by an ensemble of experiments with the expected backgorund and no true signal" [12].

That the search of CHORUS and NOMAD should yield a null result *a posteriori* was to be expected, if atmospheric neutrino data are to be believed. However, the decay search methods and emulsion scanning and analysis techniques developed by the two collaborations could prove an extremely useful *investment* for the future, especially when considering the τ appearance searches that are going to take place in forthcoming long baseline experiments [15].

2.2. $\nu_\mu \rightarrow \nu_e$ Searches

Even though the value quoted for $P(\nu_\mu \rightarrow \nu_e)$ has slightly decreased to $(0.25 \ \pm 0.06 \pm 0.04)\%$ from that originally reported [3,4], LSND remains to date the **only** experiment that claims a direct evidence for neutrino oscillations, since appearance of another flavour is observed.

This result disagrees with the simple (and perhaps desirable) interpretation of the solar and atmospheric neutrino results as $\nu_e \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_\tau$ respectively, and would lead to the introduction of a forth sterile neutrino in the mixing schemes to reconcile all experimental data. LSND has, therefore, generated both a controversy - that still remains with us - and a great deal of activity aimed at a thorough check of the experimental results.

In the parallel session we heard the latest from KARMEN 2 [14] - the natural competitor of LSND - whose findings could resolve the problem in a short time scale. Alas, it is fair to say that the results may not be conclusive, therefore experiments that will comfortably cover the LSND specified region of parameter space - such as MiniBoone at Fermilab - [3] are essential and their outcome is eagerly awaited.

KARMEN 2 is an upgrade of an earlier experiment running at ISIS, the spallation neutron facility of the Rutherford Laboratory. The major improvement consists in the instrumentation and addition of shields surrounding the detector (7000 t steel blockhouse) in order to veto cosmic rays that proved to be the principal source of background for its predecessor. In its present configuration the KARMEN2 detector has essentially three independent veto systems, with a reduction of a factor of about 40 in background resulting from cosmic rays.

At ISIS, neutrinos are produced by stopping $800 MeV$ protons in a heavy water target and beam dump. The source provides equal intensities of ν_μ's, $\bar{\nu}_\mu$'s and ν_e's (from the decay chain $\pi^+ \rightarrow \mu^+\nu_\mu$ and $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ at rest) with a small contamination of $\bar{\nu}_e$. A feature, unique to this beam, is its time structure that allows the separation of neutrinos of different flavours and helicities. This is possible because the lifetimes of pions and muons are different and $\bar{\nu}_\mu$ and ν_e originated in μ decay follow in time the ν_μ burst from π-decay.

The detector is made of 56 t of liquid scintillator, divided into 512 independent cells (viewed each by two photomultipliers) that are individually "wrapped" in Gd_2O_3 painted paper for neutron identification through a capture reaction.

$\bar{\nu}_e$ would be detected through the standard quasi-elastic reaction $\bar{\nu}_e p \rightarrow e^+ n - 1.8 \ MeV$ followed by the neutron capture with an energy release in photons of $2.2 \ MeV$ or $8 \ MeV$, depending on whether the capture occurred on a proton or a Gd nucleus.

From February 1997 to March 2000, $7160C$ of protons on target, corresponding to about $2 \cdot 10^{22} \ \pi^+$ decays, were collected. The capability and efficiency of the experiment to detect electrons was tested through the control reaction $\nu_e \, {}^{12}C \rightarrow e^- \, {}^{12}N_{g.s.}$, whose signature is quite distinctive. The energy released by the *prompt* electron is followed, within a typical decay time (16 μs) by the detection of the energy deposited by a spatially correlated positron from ${}^{12}N_{g.s.} \ \beta^+$-decay. [4] From the observation of 274 signal sequences generated by this type of ν-Nucleus charged current interaction when 281 were expected, one could conclude that efficiency calculations are reliable. Also the energy and time distributions agree with expectations. This gives confidence in the capability of $\bar{\nu}$ detection and therefore sequences attributed to the quasi elastic reaction $\bar{\nu}_e p$ can be simply counted. 11 of these were observed with an expected background of 12.3 ± 0.6 from various sources (cosmic rays:3.2; ν_e induced: 3.9; random sequences: 3.5; $\bar{\nu}_e$ contamination:1.7).

An additional signal of 9 events would be expected if oscillations occurred with LSND probability and $\Delta m^2 = 100 \ eV^2$. On the other hand, the expectation would be smaller for different values of Δm^2. The limit obtained with a *unified ap-*

[3] For a recent update, see P. Spentzouris talk at this Workshop

[4] Of course one could test $\nu_\mu \rightarrow \nu_e$ oscillation hypothesis by analysing the same reaction for events that are in time with the pion burst.

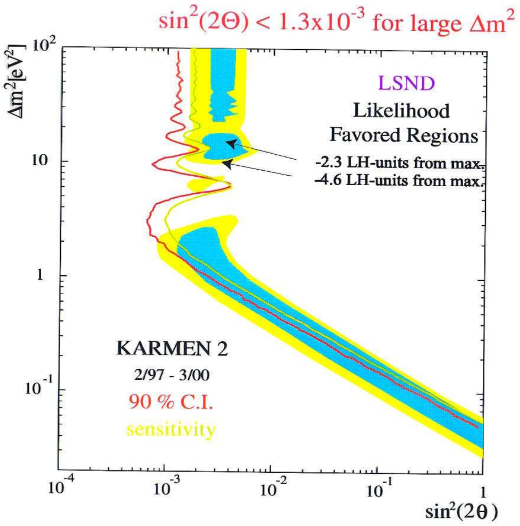

Figure 2. Limits obtained by Karmen2 and sensitivity curve. Shown are also the signal regions of LSND.

proach analysis is shown in fig. 2 superimposed on the latest values from LSND. We again observe that this is more stringent than the *sensitivity*. Furthermore, it would be interesting to know of any development of the combined analysis of LSND and KARMEN2 data, reported in the past, that did not appear to be so stringent.

3. Long Baseline Experiments

It is superfluous to stress the importance of the forthcoming long baseline experiments. Their tasks are clearly defined and may be summarised to

- address, in a controlled manner, the region of interest indicated by atmospheric neutrino data;
- establish, beyond doubt, which flavours are involved, including - if necessary - a sterile neutrino;
- measure with some degree of accuracy ($\sim 10\%$) mixing angles and mass differences.

Even though it is often stated that the atmospheric neutrino results favour $\nu_\mu \to \nu_\tau$ transitions, E. Lisi, in his review of the possible scenarios [16], pointed out that a more general situation is still allowed by the world data, thus emphasising the relevant role of future accelerator experiments. This foresees oscillations of both ν_e (solar) and ν_μ (atmospheric) into an approximately equal mixture of ν_τ and ν_s and therefore of active and sterile channels.

With the exception of K2K, discussed in the plenary session, the existing scenario for long baseline experiments [5] is shown in table 2.

	USA	**Europe**
Site	Soudan Mine ($L = 730\ km$)	Gran Sasso ($L = 732\ km$)
Beam	FNAL	CERN
Energy $< E >$ (GeV)	*Tunable* 3 (Peak)	*Fixed* 17
Proposed	1989	1996
Detectors	MINOS THESEUS	OPERA ICARUS
Method	Disappearance	Appearance
Data taking	10/2003	05/2005

Table 2
Planned long baseline experiments.

It is encouraging to observe that the experiments listed in the table proceed more or less according to the foreseen schedule, as reported by V. Paolone and A. Ereditato [17,15]. We shall briefly outline the status of these projects.

3.1. FNAL beam to Soudan Mine

Disappearance is the method chosen for the detection of oscillations in long baseline experiments in the US.

[5] THESEUS is the new name chosen for a possible extension of the lifetime of the Soudan 2 detector. Briefly digressing, one would notice that an intriguing connection across the Atlantic has been realised by that choice. In Greek mythology in fact Theseus killed the son of Minos in a place designed by the father of Icarus! Is there some profound Freudian meaning in the way acronyms are chosen?

Neutrinos are produced using the Main Injector at Fermilab [5] and three different spectra are available, with energies peaking at $3, 9, 15$ GeV and a high energy tail. In this sense this beam is "tunable", although the change in energy implies a shift in the position of the magnets and therefore time is needed for the operations that should not be thought as being *online*.

In view of the results from K2K, the *low energy* option has been chosen for the start of data taking. $3.6 \cdot 10^{20} p/year$ will be delivered and the rate of charged current interactions per $10^{19} p.o.t.$ at the Soudan mine is computed to be 12.4 for a detector of 1 $kton$.

Two detectors of mass 980 t and 5400 t respectively will be installed in two locations at ~ 900 m and 730 km from the neutrino source, in a pit and a cavern (at the Soudan mine) that are being excavated.

The MINOS "far" detector is a tracking calorimeter of octagonal shape, in which 486 layers of magnetised steel ($B \sim 1.3T$) interleaved with $4cm$-wide scintillator strips, are arranged in two sections. Each end of the scintillator strips is read out by wave length shifting fibres grouped in modules. The MINOS "close" detector is made of 282 modified octagon planes, 20% of which are fully instrumented while the rest is only partially read out.

The tests on the the scintillator system and its readout have been successfully completed and a 4-plane prototype of the far detector has already been assembled and its performance studied.

Three separate tests would enable MINOS to detect the presence of neutrino oscillations:

- ν_μ CC interaction rate comparison between close and far detector.
- ν_μ CC Energy spectrum studies.
- NC/CC comparison

They have different discriminating power but all rely on a classification of the events into *charged* or *neutral* current (indicating here simply the presence or the absence of a muon in the final state). This is achieved by measuring the event *length*, that is the distance spanned in the longitudinal beam direction, exploiting the penetrating power of muons: events with a μ in the final state will be *long*, while the others would not. The second of the methods listed would allow a measurement of Δm^2 and mixing angle, while the third is less sensitive to differences in neutrino fluxes between the close and far detectors. With reference to this point, it should be mentioned that the installation of the so called hadronic *hose* (a wire carrying current) is being investigated to increase the similarity between the two spectra and also the event rate. During the discussion, it was stressed the interest in an absolute NC rate comparison between the close and far detectors (in a sense MINOS with the NUMI beam would be like SNO with solar neutrinos, measuring the flux of all types of neutrinos). The high energy tail of the beam may limit this kind of measurement, however. Some of the results that may be obtained with MINOS are illustrated in fig. 3, while in fig. 4 is shown the accuracy that can be achieved in the determination of the mixing parameters, which depends on the initial ν energy spectrum.

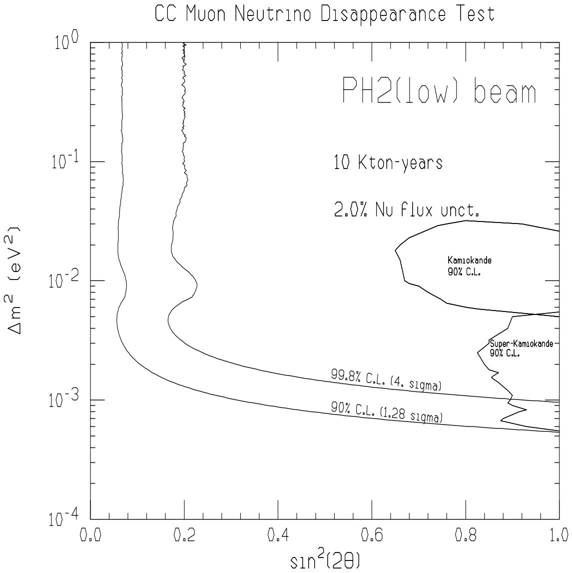

Figure 3. Sensitivity of MINOS to the disappearance of ν_μ.

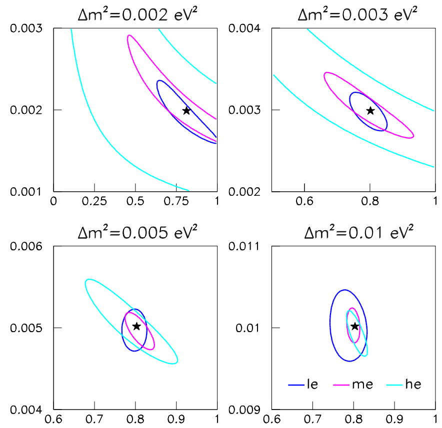

Figure 4. 68% C.L. contours in the measurement of the mixing parameters obtainable in MINOS for the values of Δm^2 indicated and different options for the beam energy spectrum

$\nu_\mu \rightarrow \nu_e$ transitions are not simple to detect in MINOS. However the possibility to use the Soudan 2 detector (re-christened Theseus) for its electron identification capabilities has been considered and preliminary results were shown at the meeting [17].

3.2. CERN beam to Gran Sasso

The civil engineering has already started for the construction of a neutrino beam from CERN to the Gran Sasso Laboratory (CNGS) in Italy [6,15]. It is tuned for ν_τ-**appearance** searches, hence the average energy of 17 GeV, well above τ production threshold. In the so called "shared" mode of operation, $4.5 \cdot 10^{19}$ protons per year would be delivered on target; 10^{19} protons on target would yield a rate of 544 ν_μ CC interactions per kiloton of detector.

A number of proposals have been considered, but OPERA [18] and ICANOE/ICARUS [19] are clear front runners, with the former already recommended for approval by the appropriate committees.

ICANOE/ICARUS [6] will identify τ through its decay $\tau \rightarrow e\nu_\tau\bar{\nu}_e$ using kinematics criteria, similar to those adopted in NOMAD. OPERA plans to observe the decay of τ's in nuclear emulsions in a scheme which is similar but not identical to that of CHORUS.

We shall briefly review here the salient points of the two projects, referring for details to the presentation by A.Ereditato at this meeting or the technical proposals [15,18,19].

ICARUS, a liquid argon imaging TPC, is too well known a detector to have to be described here. Suffice it to say that after many years of research and development of the technique of charge drifting in large volumes, it has evolved from small scale prototypes (one of $50l$, that observed interactions in a neutrino beam, and one of 10 m^3, in which trajectories from cosmic rays were reconstructed) to an almost full size module. The problems related to the cryogenics of a large vessel have been overcome thanks to a close collaboration with specialised industries and the first module of 600 t mass (T600) is to be installed in the Gran Sasso Laboratory early in the year 2001. In the configuration that is proposed to detect ν oscillations, ICANOE/ICARUS consists of four super-modules, each made out of four adjacent T600 type modules, and is equipped at the end of each super-module with a calorimeter/spectrometer (NOE) [19] whose function is to measure the energy leakage from the liquid argon part and determine the muon charge and momentum. As already stated $\tau \rightarrow e\nu_\tau\bar{\nu}_e$ is the privileged channel for oscillation studies, although the claim is that such a massive and fine grained detector would in principle be capable of contributing to other domains of physics, including atmospheric and solar neutrinos and proton decay. Restricting ourselves to the long baseline exposure of the detector, with a total fiducial mass of about 5000 t and four years of running ($1.8 \cdot 10^{20} p.o.t.$) the number of events shown in table 3 would be recorded in the absence of oscillations. The number of ν_τ CC interactions is also given for different

[6] The submitted proposal is called ICANOE. However the part of the collaboration traditionally identified with the NOE calorimeter has withdrawn from the experiment, hence the ambiguity in name.

values of Δm^2.

Process	**Liquid target**
$\nu_\mu CC$	54300
$\bar{\nu}_\mu CC$	1090
$\nu_e CC$	437
$\bar{\nu}_e CC$	29
νNC	17750
$\bar{\nu} NC$	410
$\nu_\tau CC, \Delta m^2 (eV^2)$	
1×10^{-3}	52
2×10^{-3}	208
3.5×10^{-3}	620
5×10^{-3}	1250
7.5×10^{-3}	2850
1×10^{-2}	4330

Table 3
Interactions in the ICARUS detector.

For $\Delta m^2 = 3.5\ 10^{-3}\ eV^2$, out of $620 \nu_\tau$ interactions, 35 events would be observed in the liquid target, with a background of about 6 from conventional neutrino sources.

In the discussion, a few points were debated. In particular, the interest focussed on whether the NOE spectrometer was going to be replaced by another (less efficient?) device and if the liquid argon modules could be made larger to reduce the dead space.

Technical successes have characterised the most recent history of ICARUS and this constitutes a good omen for the future. However, a realistic time scale for the full detector is difficult to predict at this stage. In any case, the presence, even at later times, of a detector of ICARUS size and capability at the Gran Sasso, could prove invaluable, especially if nature decides that there is a compelling need to investigate $\nu_\mu \rightarrow \nu_e$ oscillations using low energy neutrinos. It would be hard to imagine a detector better suited for the purpose than a **working**, massive ICARUS!

Without doubt OPERA may be defined as the ultimate appearance experiment at (or even a little beyond) the frontier of the emulsion technique. In the detector, a heavy material (Pb) is used as neutrino target while interleaved emulsion layers are used as tracking devices. This technique - traditionally known as Emulsion Cloud Chamber - is well established; however it has never been adopted on the scale planned in OPERA.

A sequence of Pb/Emulsion film [7] repeated 56 times, for a total of $10 X_\circ$, and 12 $cm \times 10\ cm$ transverse dimensions, is packaged in the so called *brick*, which constitutes the OPERA detector unit. Bricks are then arranged into *walls*; a wall is followed by a plane of orthogonal scintillator strips and together they form a target module. 24 modules are grouped into a "supermodule" followed by a magnetic spectrometer for muon identification and momentum measurements. In the current configuration the whole OPERA detector envisages the construction of three such supermodules.

The principle at the basis of the identification of τ decays is very simple and it is illustrated in fig. 5.

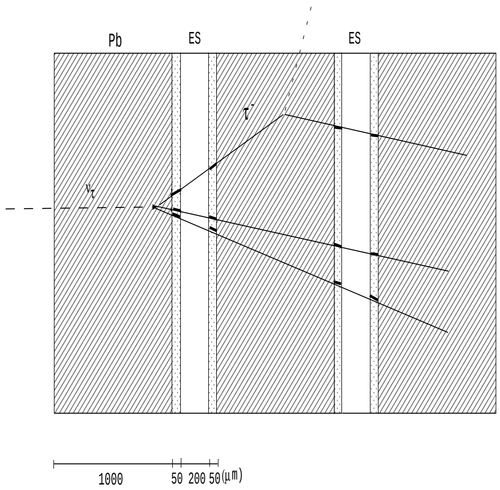

Figure 5. Principle of τ detection in OPERA.

[7] The Pb plate is 1 mm thick, while the emulsion film is made out of two layers $50 \mu m$ thick mounted on a plastic support of $200 \mu m$.

The idea is to establish whether there is an angular mismatch between the trajectories - measured in the thin emulsion layers - of the parent τ and one of its charged decay products (e, μ, h). In practice, the sequence of operations is the following:

- An approximate location of the interaction point is determined by means of the scintillator trackers;
- the brick in which the interaction occurred is extracted (its replacement is not foreseen, therefore the detector mass slightly decreases with time);
- the emulsion films are scanned for an accurate vertex location;
- the search for the decay is performed;
- particle identification and event kinematics (including momentum determination in emulsion through Coulomb multiple scattering) is implemented for a selected sample.

The phase of emulsion scanning is the most time consuming. A surface of $\sim 250cm^2/brick$ needs to be searched. The total would amount to a scanning effort that is one hundred times that invested in CHORUS. The collaboration is very confident however that this could be achieved, in view of the development of faster (by a factor of about 20) new hardware and of the increase in the number of scanning stations available for the experiment.

The decay search is extended to all single-prong decay modes of the τ, with a total detection efficiency estimated to be 8.7% (including branching ratios). This efficiency varies between 1.3% and 3%, it is largest if the decay occurs in a plate located downstream of that of the main interaction vertex (39% of all τ decays), and depends upon the selected decay channel. The expected numbers of τ's that would be detected under various hypotheses, together with background events collected in five years of data taking $(2.5 \times 10^{20} pot)$, are shown in table 4.

$\Delta m^2 (10^{-3} eV^2)$	1.5	3.2	5.0	bkg
$\tau \to e$	1.7	7.7	18.5	0.19
$\tau \to \mu$	1.3	5.7	13.8	0.13
$\tau \to h$	1.1	4.9	11.8	0.25
Total	4.1	18.3	44.1	0.57

Table 4
Detected τ's in OPERA.

A total of $\sim$ 18 events would be expected for the values of mixing parameters currently favoured by SuperKamiokande. When taken together with the bounds from that experiment, the results of OPERA would determine the mass difference within the limits indicated in table 5.

$\Delta m^2 (10^{-3} eV^2)$	1.5	3.2	5.0
Upper limit	2.1	3.8	5.6
Lower limit	0.8	2.6	4.3
(U-L)/True	41%	19%	12%

Table 5
$90\% CL$ in the determination of Δm^2 in OPERA.

In the absence of a signal, OPERA would be sensitive to $\nu_\mu \to \nu_\tau$ oscillations in the region shown in fig. 6. 90% CL limits on $\Delta m^2 < 1.2 \times 10^{-3} eV^2$ at full mixing and $sin^2 2\theta < 6 \cdot 10^{-3}$ for large mass differences would be derived in this case.

The statistics above are such that OPERA would indeed become a very difficult experiment, should smaller values of Δm^2 be favoured by SuperKamiokande and K2K. We cannot tell at this moment whether the feature that makes OPERA unique, i.e. its ability to *visually* observe decays of the τ - thus proving flavour oscillations, even to the most skeptical - would in the end result in a limitation for the experiment. For this reason, the OPERA proponents are investigating ways of extending its scope.

With both disappearance and appearance projects being pursued and data taking promised to begin in the years 2003-2005, we should feel

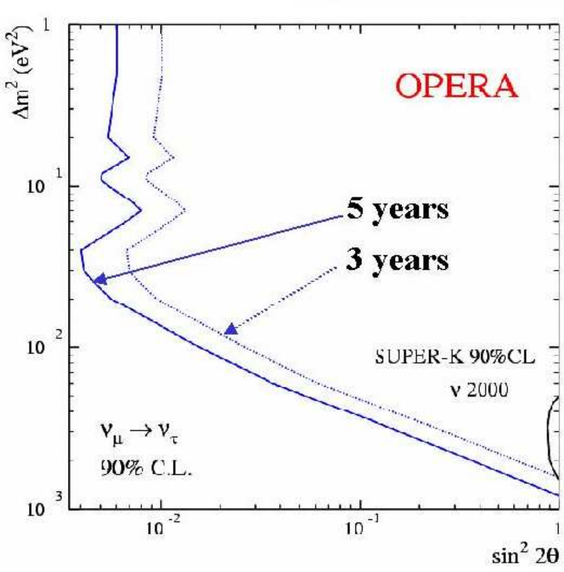

Figure 6. Sensitivity to $\nu_\mu \rightarrow \nu_\tau$ oscillations of the OPERA experiment in the absence of a signal.

quite confident that the next generation of long baseline experiments will disentangle the mixing of ν_μ's and measure the oscillation parameters, provided that Δm^2 is not much below $10^{-3} eV^2$. The importance of possible $\nu_\mu \rightarrow \nu_e$ oscillations is not underestimated and steps towards measurements in that area are actively considered.

4. Precision Measurements

It was pointed out [16] that the most natural schemes in which to discuss mixing among neutrinos are those that include **all** the families that are known to exist. Models that consider three and four neutrinos are therefore conceivable at present, the latter being justified by the uncertainty on the very existence of a ν_s. This ambiguity will most likely be removed with the completion of MiniBoone (2003?), however.

For a thorough review of popular 3ν and 4ν models we refer to the presentations by E.Lisi and C. Giunti [16,20], recalling here only the general features.

Regardless of the mixing scheme adopted, the following two points are addressed:

- What is the hierarchy in the mass scale?
- Which are the entries in the mixing matrix that are completely unknown or need to be measured with better accuracy?

As far as the mass ordering is concerned, in three neutrino schemes, with the identification $\Delta m^2_{12} = \Delta m^2_{sol}$ and $\Delta m^2_{13} \simeq \Delta m^2_{23} = \Delta m^2_{atm}$, it would be necessary to establish whether the hierarchy is "*natural*" (i.e. $m_1 < m_2 << m_3$) or "*degenerate*" ($m_3 << m_2 < m_1$). The number of possible situations increases in models with four neutrinos and a mass scale Δm^2_{LSND} should be accommodated. It is interesting to observe that there is already some "sensitivity" to present data. The revival of the so called $(3+1)$ schemes [16,20] caused by the revised and slightly reduced value of $P(\nu_\mu \rightarrow \nu_e)$ quoted by LSND, is a point in case. This, if nothing else, is a symptom of how difficult it is to obtain "predictions" from theory on the subject of neutrino masses and mixing and emphasises the experimental nature of the field.

The mixing among n light species is described by a unitary $n \times n$ matrix that will contain three angles and one phase, if $n = 3$, or six angles and three phases, if $n = 4$. [8] For the case of three neutrinos, the unitary matrix U, expressing the mixing $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$, may be written as three successive rotations $U = R(\theta_{23}) \cdot R(\theta_{13}, \delta) \cdot R(\theta_{12})$, with

$$R(\theta_{23}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad (1)$$

$$R(\theta_{13}, \delta) = \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \quad (2)$$

$$R(\theta_{12}) = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3)$$

where $c_{ij} = cos\theta_{ij}$ and $s_{ij} = sin\theta_{ij}$, and the CP-phase δ is included as a complex rotation in the $1-3$ subspace.

[8] If neutrinos are Majorana particles there will be six phases, but three of them are not observable in oscillations.

Experimentally, atmospheric and long baseline projects will determine, hopefully with a precision of order of 10%, the parameters contained in $R(\theta_{23})$, and solar and reactor experiments [7] will soon cover the region of parameters included in $R(\theta_{12})$. $R(\theta_{13}, \delta)$ is the least known so far: our ignorance of δ is total and the current limit on θ_{13}, from a fit to the SuperKamiokande and CHOOZ data, is $sin^2\theta_{13} < 0.02$ [21]. Improvements may take some time and dedicated efforts. [9]

Therefore, it appears natural that future generations of experiments should address the specific issues of:

- measuring θ_{13};
- determining the mass ordering;
- establishing whether there are visible CP-violation effects in the leptonic sector and measuring δ (if possible).

These tasks would essentially remain unchanged in 4ν mixing schemes, only there would be more parameters to measure in that case [22].

4.1. Sign of Δm^2 and θ_{13}

Effects that might be attributed to the action of the MSW mechanism have never been observed on a terrestrial scale and to do so would be interesting in its own right. However "matter" may be used also to determine the **sign** of Δm^2 and measure θ_{13} [23] (in three neutrino mixing, the mass difference under consideration is Δm^2_{Atm}, explicitely $\Delta m^2 = m_3^2 - m_2^2 \simeq m_3^2 - m_1^2$).

This is in principle possible since the oscillation parameters in vacuum should be modified when neutrinos travel in matter. In particular, for the mixing angle one would obtain the expression

$$sin^2 2\theta_{13,m} = \frac{sin^2 2\theta_{13}}{\left(\frac{2EV}{m_3^2 - m_1^2} - cos2\theta_{13}\right)^2 + sin^2 2\theta_{13}} \quad (4)$$

where $V = \sqrt{2} G_F N_e$ is the usual matter term (that depends on the density) and has opposite sign for ν and $\bar{\nu}$. It has been pointed out [24], that the mixing in matter is sensitive to the **sign** of the mass difference, the largest effect being obtained under the resonant condition $2EV = (m_3^2 - m_1^2)cos2\theta_{13}$ [23], although experimentally it is not easy to achieve. The transition probabilities $P(\nu_\alpha \to \nu_\beta)$ are modified as well (see [23] for details) and -as it is shown in fig. 7 - may produce $\nu - \bar{\nu}$ asymmetries in $\nu_e \to \nu_\mu$ transitions, while the effect of matter is negligible for $\nu_\mu \to \nu_\mu$ transitions.

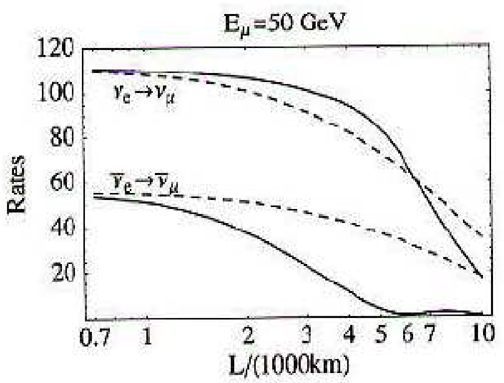

Figure 7. Comparison of $\nu_e \to \nu_\mu$ transitions with (solid line) and without (dashed line) the inclusion of the effects of matter.

Qualitatively, if $\Delta m^2 > 0$, $\nu_e \to \nu_\mu$ are enhanced and $\bar{\nu}_e \to \bar{\nu}_\mu$ are depleted, while the opposite is true for $\Delta m^2 < 0$. The potential of the application of this method to experiments at neutrino factories, was thoroughly investigated by Lindner [23] using as reference a detector located at a distance of $7332km$, which may or may not have charge identification capability. The key observation is that matter effects induce sizeable asymmetries even in the total rate of the observed muons (i.e. without distinguishing the charge) and this rate depends on the sign of the mass difference. Furthermore, since matter enhanced oscillations depend on the neutrino energy, indirectly they affect the spectrum of the observed muons. A two parameter fit to this spectrum, in

[9] In the ICANOE proposal [19], it is stated that a $20kton$-year exposure of ICARUS would improve the limit by one order of magnitude; the time scale for such an exposure is uncertain, however.

the *appearance* channel [10] , could allow extraction of both Δm^2 and $\sin^2 2\theta_{13}$, once the absolute value of Δm^2 is constrained from an analysis of the combined appearance and disappearance channels. Under assumptions concerning the detector, considered somewhat optimistic during the discussion, values of $sin^2\theta_{13}$ as low as $5 \cdot 10^{-3}$ are claimed to be accessible. Also the sign of Δm^2 may be measured with a detector that has no charge identification provided that $sin^2\theta_{13}$ is not too small (10^{-2}).

4.2. CP violation effects

CP asymmetries would manifest themselves in a non zero value of the ratio

$$A_{e\mu} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} \tag{5}$$

In three flavour mixing, the CP-odd transition probability is given by the expression

$$\pm 2J\left[sin\Delta_{12} + sin\Delta_{23} - sin\Delta_{13}\right] \tag{6}$$

where the positive and negative sign refer to ν and $\bar{\nu}$ respectively, $\Delta_{ij} = \left(\frac{\Delta m^2_{ij} L}{4E_\nu}\right)$ and $J = c_{12}s_{12}c^2_{13}s_{13}c_{23}s_{23}sin\delta$.

With obvious approximations, the CP violating transition probability will be proportional to

$$\left(\frac{\Delta^2_1 L}{4E_\nu}\right) sin^2\left(\frac{\Delta^2_2 L}{4E_\nu}\right) \tag{7}$$

where Δ^2_1 and Δ^2_2 are the mass differences suggested by the solar and atmospheric neutrino solutions, that is $\Delta^2_1 = \Delta m^2_{sol}$ and $\Delta^2_2 = \Delta m^2_{atm}$.

In models with mixing among four families, the existence of a mass difference of order of $1eV$, as suggested by LSND, is required. Then, in the formula above, the scales change: $\Delta^2_1 = \Delta m^2_{atm}$ and $\Delta^2_2 = \Delta m^2_{LSND}$, and CP-violating effects would therefore become "*easier*" to measure, in a sense that is discussed later.

Even if the preferred solar neutrino solution is the LMA (any other would make **impossible** the already formidable task of measuring the phase δ), the asymmetries introduced by the effects of matter should be disentangled from those due to CP-violation. The correct choice of the energy of the incident neutrinos may be the key to the solution. In one of the options available, high energy beams from neutrino factories are considered [25]. In this case the detector will have to be placed at distances of the order of $1000km$, and matter asymmetries will be much larger than those from CP-violation. However, the two have a different L/E behaviour and in principle they may be disentangled by changing L (detectors at different positions) or by changing E (detectors with good energy resolution) or both. The claim is that, with a $40kton$ magnetised iron detector at a distance of $3500km$, maximal phase $|\delta| = 90°$ may be distinguished from $\delta = 0$ in five years of running, provided that $\Delta m^2_{12} > 2 \cdot 10^{-5} eV^2$ [25]. Another option would be to consider low energy beams with $E \sim 100 - 200MeV$, [26,27] which in turn would imply detectors placed closer to the neutrino source ($L \sim 100 - 200km$). These two conditions are instrumental in making matter and CP effects of about the same order of magnitude, as it is illustrated in fig. 8 This is clearly an interesting alternative, though the detection of low energy neutrinos and the monitoring of their

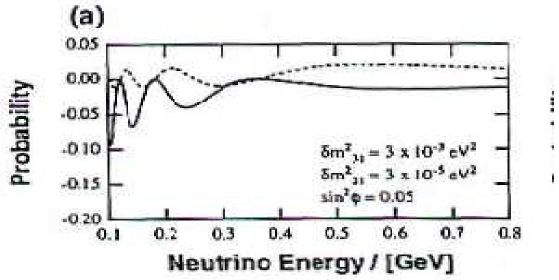

Figure 8. Comparison of matter (dashed line) and CP-Violating (solid line) effects as a function of the neutrino energy. The values of other relevant parameters are indicated.

[10] *Appearance* (*disappearance*) with neutrino beams from μ decays is the channel in which the muons that are considered have sign of charge opposite (identical) to those that decayed.

fluxes may not be straightforward.

As mentioned earlier, measuring CP-violation effects would be comparatively "*easier*" if a sterile neutrino existed. In this case a detector may be placed at a distance of order of $10km$, where, again, matter effects become less important. Since CP-asymmetries appear to be largest in channels involving ν_τ's [25,28], measurements are also suggested that envisage the use of a $1kton$ detector with τ identification capabilities.

4.3. New Neutrino Sources

We have seen that for the detection of effects due to the violation of CP, it is essential to avoid, or at least minimise, flavour contamination in the beam. This requirement imposes constraints on the possible sources of neutrinos, be of novel or old conception. The options were reviewed and their relative merits discussed in what resulted to be an extremely lively debate. This touched not only upon the ability of the various machines to address issues related to CP-violation in the leptonic sector, but also considered their physics reach in more general terms, although neutrino mixing and accurate measurements of mass differences and mixing angles played the lead role [27].

A number of options have been considered by working groups in Europe, USA and Japan, although it is correct to say that not all of them are at the same level of development. These are:

- Neutrino Factories.
- "Conventional" (i.e. from π and k decays) superbeams (high energy)
- Low Energy superbeams.
  - Narrow Band
  - Low Energy Muons

The studies on neutrino factories are well advanced (for an update, see the talks by B. Autin and A. Blondel at this Workshop). They are the first step towards the design of muon colliders and it is the decay of μ's, of momentum typically between 20 and 50 GeV, in straight sections of a dedicated storage ring, that generates neutrinos.

Many are the advantages a neutrino beam from μ decay, suffice it to mention the absolute knowledge of flavour composition, the well know energy spectrum, and the high intensity. Several conceptual designs (of various shapes [27,29,31]) exist for such a machine. Both engineering studies and tests for new types of targets are being conducted and necessary precursor experiments (cooling) are being prepared. Also, more efficient schemes or completely new concepts of particle acceleration are not being neglected [29]. Neutrino factories are effectively the reference against which the other proposals should compare. They indeed could allow precision measurements of many parameters of the neutrino mixing matrix, using transitions originated by both ν_e's and ν_μ's. It is correct to point out however that if the solar neutrino solution is not that with large angle, then CP-violation effects would be out of reach, even for neutrino factories. It is worth to mention at this point that a sort of neutrino factory of a moderate beam intensity may be realised by upgrading PRISM, an existing facility. This is a source of high-intensity, low-energy ($p_\mu = 68MeV$) muons used for studies of rare decays. The addition of another accelerator will allow $10^{20}\mu/10^7s$ to be stored in the ring for the production of neutrinos [27].

Low energy conventional beams have been considered for their appeal, in terms of cost and time, when compared to neutrino factories. The energy of the primary particles is chosen to be below the threshold for K production, to reduce the ν_e contamination in the beam.

A narrow band beam, with mean neutrino energies around $1-2\,GeV$, has been suggested [30], as an alternative to neutrino factories, to determine the parameters of interest with a $20kton$ detector located 732 km away. The claim is that values as low as $\Delta m^2_{12} = 4.2 \cdot 10^{-5}eV^2$, $sin^2\theta_{13} = 4 \cdot 10^{-3}$ (for $\Delta m^2_{12} = 2 \cdot 10^{-4}eV^2$) and $|sin\delta|_{min} = 0.35$ may be reached [30]. Even though some skepticism was expressed concerning the obtainable fluxes (the assumptions were considered to be too optimistic), this option is going to be further investigated, in conjuction with the possibility of using a 2.2 GeV proton LINAC at CERN.

Furthermore, the proposal to obtain neutrinos through the standard production and decay chain, using the Japan Hadron Facility (JHF) is under serious consideration. The proton flux at JHF is expected to be about one hundred times that of the KEK protosynchrotron and a $1Mton$ water Cerenkov detector is suggestd for ν_e detection at a distance of about $100km$ [26].

The consensus at the meeting was that, although neutrino factories appear to have better performances, conventional beams are worth investigating, extending the study to other aspects - like the design of detectors - that have been neglected so far.

5. Conclusions

Great expectations surround *laboratory* neutrinos. In summary, as far as the current generation of experiments is concerned:

- The searches for $\nu_\mu \rightarrow \nu_\tau$ oscillations by CHORUS and NOMAD in the cosmologically interesting region have yielded a negative result. This, *a posteriori* might have been expected.

- In the $\nu_\mu \rightarrow \nu_e$ channel, KARMEN2 has not completely ruled out the region favoured by LSND. The existence of a sterile neutrino is still possible.

The next generation of experiments

- Will definitely resolve this latter ambiguity concerning ν_s (MiniBoone, 2003)

- Will establish, with long baseline experiments, which are the flavours involved in the oscillations observed today in atmospheric neutrinos.

- Will measure with reasonable accuracy mass differences and mixing angle (MINOS, OPERA, 2005-2010).

And the generation after that

- Will attempt precision measurements of matter effects, θ_{13}, sign of Δm^2, and CP-violation in the leptonic sector.

- Will do the measurements above either at neutrino factories, considered as a possible new, powerful source of ν's or in conventional superbeams that are not neglected and whose role is not underestimated.

While it is difficult to predict the exact outcome, it is easy to guess that is going to be exciting!

On the subject of "predictions", perhaps some might see a reference to the results of experiments in Japan and to ν physics research, in a prophecy by Nostradamus (Cen. 5, Q. 12.): "*...and the Asiatic part will change. To near the Lake of Geneva will it be conducted...*"

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