Review on new Neutrino Oscillation Experiments

Mario Campanelli
Institut für Teilchenphysik ETHZ, CH-8093 Zürich, Switzerland

Abstract
Driven by new experimental results, in the latest period several new neutrino oscillation experiments have been proposed. I will outline the main ideas behind the different proposals, in particular concerning atmospheric neutrinos and neutrinos from accelerated beams.
1 Introduction

Neutrino physics is living a period of great excitement. Many experiment show results that point towards evidence for neutrino oscillations, and others are planned to verify with better precision or new techniques these results. In particular, the experiments observing effects difficult to explain without oscillations can be classified into three categories:

- **solar neutrinos**
  A deficit of $\nu_e$ is observed the solar neutrino spectrum. It can be interpreted as oscillations with $\Delta m^2 \approx 10^{-5} - 10^{-3} eV^2$ (if oscillation mainly takes place in the solar matter) or $10^{-9} - 10^{-10} eV^2$ (if oscillation takes place in the vacuum between the sun and the earth)

- **atmospheric neutrinos**
  the $\nu_\mu/\nu_e$ ratio is lower in the data than in the expectations; it can be interpreted in a disappearance of $\nu_\mu$, governed by oscillations with $\Delta m^2 \approx 10^{-3} - 10^{-2} eV^2$

- **LSND**
  the LSND experiment at Los Alamos observes an excess of electrons in a $\nu_\mu$ beam. If interpreted as neutrino oscillation, the mass difference would be $\Delta m^2 \approx 1 eV^2$

Three neutrino families have only two possible mass difference scales, so it is difficult to accommodate the present experimental data without either stretching them, discarding one result, or assuming new phenomena, like the existence of sterile neutrinos not coupling to the Z.

2 Atmospheric neutrino results

Neutrinos are produced in the atmosphere from $\pi^\pm \rightarrow \mu^\pm \nu_\mu$ and subsequent $\mu^\pm \rightarrow e^\pm \nu_e \nu_\mu$ decays. The calculations of absolute fluxes have uncertainties of the order of 30%, so what is usually used is the quantity $R = \frac{\Phi_{\nu_e} + \Phi_{\bar{\nu}_e}}{\Phi_{\nu_\mu} + \Phi_{\bar{\nu}_\mu}} \approx \frac{1}{2}$ where most of the uncertainties cancel out, leading to an error of about 5%.

The atmospheric neutrino experiments are detecting electrons or muons produced in charged-current neutrino interactions, using calorimeters or water Cherenkov devices. The results obtained for the double ratio by the different experiments, are shown in table 2. The statistical accuracy of the latest measurements of the SuperKamiokande collaboration is extremely good, given the large mass of the detector, so the statistical error is smaller than the systematics due to the uncertainties on the double ratio, and even with more data no further improvement is foreseen.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Exposure (Kton-year)</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperK subGeV</td>
<td>45</td>
<td>0.67 ± 0.02 ± 0.05</td>
</tr>
<tr>
<td>SuperK multiGeV</td>
<td>45</td>
<td>0.66 ± 0.04 ± 0.08</td>
</tr>
<tr>
<td>IMB</td>
<td>7.7</td>
<td>0.54 ± 0.05 ± 0.11</td>
</tr>
<tr>
<td>Kamiokande subGeV</td>
<td>7.7</td>
<td>0.60 ± 0.06 ± 0.07</td>
</tr>
<tr>
<td>Kamiokande multiGeV</td>
<td>7.7</td>
<td>0.57 ± 0.08 ± 0.08</td>
</tr>
<tr>
<td>Soudan-II</td>
<td>4.2</td>
<td>0.66 ± 0.11 ± 0.06</td>
</tr>
<tr>
<td>NUSEX</td>
<td>0.4</td>
<td>0.96 ± 0.32 ± 0.28</td>
</tr>
<tr>
<td>Fréjus</td>
<td>2.0</td>
<td>1.00 ± 0.15 ± 0.08</td>
</tr>
</tbody>
</table>

Table 1: Double ratio $(N_\mu/N_e)_{\text{Data}}/(N_\mu/N_e)_{\text{MonteCarlo}}$ for different atmospheric neutrino detectors. The first five values refer to water Cherenkov detectors, the last three to calorimeters. Of the errors quoted, the first is statistical and the second systematical.

Before reaching a detector paced close to the surface, neutrinos produced in the atmosphere can travel distances ranging from about 10 km (neutrinos coming from above) to about 100000 km (neutrinos coming from below, that crossed the whole earth diameter before reaching the detector). Therefore, a measurement of the zenith angle of the neutrino direction can be converted into a measurement of the distance $L$ between neutrino production and detection. Since the oscillation probability depends on the ratio $L/E$, if the oscillation hypothesis is correct the $\nu_\mu$ deficit should not be uniformly distributed in azimuthal angle, but in the case of small probability be larger for neutrinos coming from below and smaller for those coming from above. The fact that this effect
is actually observed by the SuperKamiokande collaboration (see figure 2), supports the oscillation hypothesis. The disappearance of muon neutrino observed in the SuperKamiokande experiment is therefore well-established, and it is likely to be due to oscillations. In case it is interpreted as an indication of \( \nu_\mu \rightarrow \nu_\tau \) oscillation, the best fit of the observed distribution yields a value of \( \Delta m^2 \) between \( 1.5 \times 10^{-3} \) and \( 8 \times 10^{-3} eV^2 \) at 90% C.L., with mixing angle close to maximum. The \( \chi^2 \) from this fit is \( \chi^2_{\nu_\mu \rightarrow \nu_\tau} = 62.1\;/\;67\;DOF(P = 65\%) \).

Other interpretations are possible:

- \( \nu_\mu \rightarrow \nu_e \) this possibility is ruled out by the result of the Chooz experiment looking for \( \nu_e \) disappearance; the ratio observed/expected events is \( 0.98 \pm 0.04 \pm 0.04 \), thus excluding \( \nu_e \rightarrow \nu_x \) in the case of maximal mixing for \( \Delta m^2 > 9 \times 10^4 eV^2 \). Also the fit of the Superkamiokande distribution seems disfavoring this hypothesis: \( \chi^2_{\nu_\mu \rightarrow \nu_e} = 110\;/\;67\;DOF(P < 0.1\%) \).

- \( \nu_\mu \rightarrow \nu_s \) The SuperKamiokande fit leaves this possibility open (\( \chi^2_{\nu_\mu \rightarrow \nu_s} = 64.3\;/\;67\;DOF(P = 57\%) \)).

More experimental indications can come from the ratio \( \pi^0/e \); in fact, the Neutral Current process \( \nu_e,\mu,\tau N \rightarrow \nu_e,\mu,\tau \pi^0 X \) does not exist for sterile neutrinos, since they do not couple to the \( Z^0 \), modifying the ratio above. The SuperKamiokande result (\( \pi^0/e \)) \( \text{data}/(\pi^0/e)_{MC} = 0.93 \pm 0.07 \text{(stat)} \pm 0.19 \text{(syst)} \) disfavors this interpretation.

### 3 Next Generation

The oscillation hypothesis for atmospheric neutrinos has to be confirmed and further investigated. The proposed future experiments can be split into two main categories: new detectors for atmospheric neutrino studies, or experiments performed with high-energy neutrino beams from accelerators. The issue can be better understood looking at the neutrino energy spectra for the different options (figure 3).

Atmospheric neutrinos have a broad spectrum (lines a and b), with their maxima around 1 GeV. Only the tail of these events reaches energies higher than the energy threshold for \( \tau \) production (about 10 GeV). Therefore, a next generation atmospheric neutrino experiment will aim at verifying...
Figure 2: Energy spectra for the two flavours of atmospheric neutrinos, as well as for the proposed long-baseline beams.

the results of SuperKamiokande using a different technique. Artificial neutrino beams, on the other hand, are designed to have most of the flux at the higher energy; the primary goal of experiments with these beams will be $\tau$ lepton identification.

3.1 Icarus at Gran Sasso

The Icarus$^2$ detector is the only next-generation atmospheric experiment currently approved. It consists in a liquid-argon TPC, with 3D imaging capabilities and very good particle identification. Given its density (1.4 $g/cm^3$) particles produce electromagnetic and hadronic showers, and, as well as a tracking device, the detector can be used as a calorimeter, with energy resolution $\sigma(E)/E = 1\% + 3\%/\sqrt{E(\text{GeV})}$ for electromagnetic showers, and $\sigma(E)/E = 15\%/\sqrt{E(\text{GeV})}$ for fully contained hadronic showers, assuming a software compensation is applied.

A 50 liter prototype of this detector was tested with neutrino of the WANF beam at CERN in years 1997 and 1998. Several neutrino interaction events have been recorded and studied, and an electron lifetime larger than 8 ms was obtained. Given the fact that the drift velocity for an electric field of 200 V/m is $1 \text{mm}/\mu\text{s}$, this step was very encouraging towards the construction of a larger detector. Presently, a 15 ton module is in operation, and the first 600 ton detector is under construction. This detector is expected to start data taking in Gran Sasso in the beginning of year 2001, and an upgrade to 2.4 ktons is foreseen in the next 5 years.

Given the rate for atmospheric neutrinos of 100 events/0.5 kton/year, after 1 year of data taking the whole SuperKamiokande suggested region can be covered, giving the first independent test of this result. It can look surprising that a small number of events can reach similar sensitivity with respect to the much larger statistics of SuperKamiokande; it is possible due to the better understanding of the final state and to the lower energy threshold, allowing to explore a smaller value of $\Delta m^2$.

3.2 Large atmospheric experiments

Future large atmospheric neutrino experiments are planned, in order to collect more statistics, in particular in the high-energy region where the uncertainties on neutrino production are smaller. New detection techniques are also proposed; the experiments can be classified into four categories:

- high density iron calorimeter (CERN-SPSC 98-28)
- lower density calorimeter with magnetic field (NICE)
- large ICARUS-like detector (SUPER-I)
- large water Cherenkov detector (AQUARICH)
Figure 3: Schematic view of a 600 ton module of the ICARUS detector

Figure 4: 90% C.L. intervals for $\nu_\mu$ disappearance from atmospheric events for different exposures of the Icarus detector.
A high-density calorimeter could be built using quite standard technologies. A large mass (i.e., 36 ktons of iron/tracker sandwich) is needed to fully contain muons from \( \nu_\mu \) interactions, and so measure their energy from the range, and their direction, which for energetic events is a good approximation of the direction of the incoming neutrino. For values of \( \Delta m^2 < 10^{-3}eV^2 \), the downward-going muons do not oscillate, and can be considered as the reference sample; upward-going muons on the other hand do oscillate; the ratio of the \( L/E_\nu \) distributions for the two samples (figure 3.2) shows a dip in correspondence of the first maximum of the oscillation probability. From the position of this dip a direct measurement of \( \Delta m^2 \) can be performed, while the depth allows a determination of the mixing angle, determining the oscillation parameters with good precision.

In 4 years of data taking, such a detector could be sensitive to \( \nu_\mu \rightarrow \nu_\tau \) oscillations with \( \Delta m^2 = 1 \times 10^{-3} \). Second plot: ratio of the above distributions, showing a clear dip in correspondence with the first maximum of oscillation probability. Third plot: accuracy of the measurement of the oscillation parameters after three years.

In 4 years of data taking, such a detector could be sensitive to \( \nu_\mu \rightarrow \nu_\tau \) oscillations with \( \Delta m^2 > 6 \times 10^{-5}eV^2 \). Given these characteristics, this approach is good only if the oscillation is governed by small values of \( \Delta m^2 \); for values of this parameters larger than \( 10^{-3}eV^2 \) almost horizontal neutrinos should be used, introducing large uncertainties; for even larger values, even the downward-going neutrinos oscillate, and cannot be considered any more a reference sample. Moreover, this kind of detector is not able to identify electron, and very poor in reconstructing the hadronic energy, restricting the events studied to a small fraction (about 10%) of the total.

A slightly different approach is using a more granular calorimeter with smaller mass (about 10 kton), surrounding it by a magnetized iron spectrometer, as proposed by the NICE group. Muon momenta can be then measured with the spectrometer, without the need of full containment; the mass can be smaller and the granularity improved, to improve the neutrino direction reconstruction through the measurement of the hadronic energy.

If more granularity should be pursued, a possibility would be to build a large detector using the ICARUS technology, and recently a proposal for a 30 kton SUPER-ICARUS has been made. This detector would have no magnetic field, but its good electron identification would open much more study opportunity than the iron calorimeters.

The only technique to have very large detectors (> 100 kton) at an affordable cost is probably the detection of Cherenkov light either in water or in ice. The Aquarich group proposed the construction of a large Ring-Imaging Cherenkov made of two concentric spheres, the inner one used as a reflecting surface, and the outer one equipped with photomultipliers to catch the light produced by the Cherenkov rings. Momentum and mass of the particles produced in the neutrino interaction are measured from the width and opening angle of the rings, and a precision \( \sigma(p)/p = O(1\%) \) could be achieved. Presently prototype tests of this detector are in progress.

### 4 Long Baseline neutrino beams

The main reasons to use neutrinos from accelerators is to have more control on the neutrino flux and composition, and to have sufficient energy to perform \( \tau \) appearance experiments. Three programs are presently competing:

- **K2K** from KEK to Kamioka (235 Km, 1999-)

![Figure 5: First plot: downward-going (hatched histogram) and upward-going (open histogram) neutrino events for \( \nu_\mu \rightarrow \nu_\tau \) oscillations with \( \Delta m^2 = 1 \times 10^{-3} \). Second plot: ratio of the above distributions, showing a clear dip in correspondence with the first maximum of oscillation probability. Third plot: accuracy of the measurement of the oscillation parameters after three years.](image)
• NuMi from FNAL to Soudan (734 Km, 2002-)
• NGS from CERN to Gran Sasso (732 Km, 2004-)

4.1 K2K

The Japanese project is the most advanced of the three, since a successful proton extraction was performed in the beginning of March and neutrino physics is expected to start very soon. A close detector will be placed close to the neutrino production for studies of flux and beam profile; the far detector is SuperKamiokande. As can be seen in figure 3, the K2K beam has lower energy spectrum with respect to its competitors, covering mainly the atmospheric neutrino region. The mean neutrino energy will be about 1.4 GeV, below $\tau$ production threshold, so only $\nu_\mu$ disappearance can be performed. After $10^{20}$ protons on target, corresponding to about 3 years of data taking, $\nu_\mu \rightarrow \nu_x$ oscillations can be tested down to $2 \times 10^{-3} eV^2$ (see figure 4.1), thus not completely covering the region indicated by the atmospherics.

Figure 6: Exclusion plot for $\nu_\mu$ disappearance after 3 years of operation of the k2k long-baseline project

4.2 High-energy beams

The American and European projects share more similarities, and both are expected to start in some years from now. A detailed comparison of the two projects (table 4.2) shows that the larger number of protons on target available in the American project is compensated by the fact that the protons from the CERN SPS are more energetic, therefore the discovery reach of the two beams is quite similar, especially if the SPS is run in dedicated mode (indicated by an asterisk).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NGS</th>
<th>NuMi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$ (GeV)</td>
<td>400</td>
<td>120</td>
</tr>
<tr>
<td>POT/year</td>
<td>$4.0 \times 10^{19}(\times 2)^*$</td>
<td>$3.7 \times 10^{20}$</td>
</tr>
<tr>
<td>$&lt; E_\nu &gt;$ (GeV)</td>
<td>26.7</td>
<td>17.6</td>
</tr>
<tr>
<td>$\nu_\mu$ CC/POT/ton</td>
<td>$4.7 \times 10^{-20}$</td>
<td>$1.0 \times 10^{-20}$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC/y/ton</td>
<td>1.9(3.8)$^*$</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Table 2: A comparison between the European and American long-baseline projects. The asterisk indicates a dedicated SPS run.
4.3 NuMi program

The American long-baseline project foresees the production of neutrinos with average energy of about 17.6 GeV from the Fermilab Main Injector, and the detection in a 5.4 kton magnetized iron plate detector (MINOS\(^7\)) placed in the Soudan mine, in Minnesota. The total event rate will be as high as \(2 \times 10^4\) charged current events per year, but the characteristics of the detector do not allow a direct identification of the \(\tau\). Therefore only \(\nu_\mu\) disappearance is possible, and the oscillation parameters are measured via the ratio of neutral over charged current events as a function of energy. At a given distance of 734 km, the first maximum of \(\nu_\mu\) oscillation probability is given by \(E_d = 594\text{GeV} \times \Delta m^2\), corresponding to 2.1 GeV for \(\Delta m^2 = 3.5 \times 10^{-3}\). This means that an optical configuration at which most of the neutrino flux is at low value has to be chosen. In this case, a good coverage of the atmospheric region can be achieved (figure 4.3).

![Figure 7: Exclusion plot for \(\nu_\mu\) disappearance using the low-energy NuMi beam.](image)

4.4 NGS program

The main point of the European long-baseline program is that it is focused on the direct detection of the \(\tau\), directly derived from the experience of \(\tau\) search in Chorus and Nomad. Two complementary approaches are possible:

- topological identification of \(\tau\) decays (kink search)
- exploit particular kinematics of \(\tau\) decays

The first approach is followed by the OPERA proposal\(^8\). The homogeneous emulsion technique to search for \(\tau\) production was successfully tested and operated in CHORUS; since the neutrino flux at Gran Sasso is much smaller, more mass is needed to have reasonable rates, and a sandwich of a glass target and emulsions sheets used for tracking is used, to achieve a final mass of 750 tons. Each lead-emulsion layer is separated by their neighbors by a 3 mm air gap (see figure 4.4), so that most of the neutrinos interact in the glass, and in case of oscillation the \(\tau\) can decay in the air gap, producing a kink visible as a large impact parameter, measured in the emulsion layers, that have a detection granularity \(O(\mu m)\).

This technique should ensure very low background levels (about 0.1 events/year), for a 90% sensitivity to values of \(\Delta m^2\) larger than \(1.5 \times 10^{-3}\) for \(\nu_\mu \rightarrow \nu_\tau\) oscillations with maximal mixing.

Another approach is to search for \(\tau\) production using kinematic criteria, exploiting the particular characteristics of \(\tau\) decays, as it is foreseen by the ICARUS collaboration. Several \(\tau\) decay channels will be used, the \(\tau \rightarrow e\) one being the cleanest. In this case the main background is coming from \(\nu_e\) charged-current interactions, which are on average more energetic and more balanced.
can be seen from figures 4.4, cutting on few kinematical variables largely improves the signal over background ratio, reaching sensitivity levels comparable to those of OPERA for a 2.4 kton detector.

Figure 9: Kinematica variables used in the $\tau \rightarrow e$ analysis in ICARUS

5 $\nu_\mu \rightarrow \nu_e$ oscillations

The LSND experiment at Los Alamos is so far the only accelerator neutrino detector to claim for positive evidence for neutrino oscillations. The detector is composed of 167 tons of mineral oil and scintillator, read by 1220 PMTs. The neutrinos are produced by Decay At Rest (DAR) or In Flight (DIF) of muons from the Los Alamos Meson Facility, and their mean energy is around 50 MeV, for a distance between production and detection of about 30 m.

In particular, LSND reports positive evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations in the following channels:

- $\bar{\nu}_e p \rightarrow e^+ n$, $np \rightarrow d\gamma (2.2 \text{ MeV})$ (DAR)
  a $e^+$ tag comes from Cherenkov and scintillation light, in delayed (180 $\mu$s) coincidence with a neutron tag
• $\nu_e C \rightarrow e^- X$ (DIF)
  $e^+$ tag from Cherenkov and scintillation
• $\nu_e^{12}C \rightarrow e^- + ^{12}N_{gs}, ^{12}N_{gs}/\beta$ decay (DIF)
  double, correlated $e^- e^+$ tag

Since 1997 the Karmen2 experiment is running at RAL to verify the LSND claim. They expect a total background of 7.8 events, mainly coming from cosmic rays (1.7 ev.), $\nu_e$ in $\mu$ decays (2.6), accidentals (2.0) and $\bar{\nu}_e$ beam contamination (1.5), and 8 candidates are observed. As can be seen from figure 5, only a part of the LSND allowed region can be covered, and even more statistics will not fully verify the LSND result.

Other new experiments are planned to verify $\nu_\mu \rightarrow \nu_e$ oscillations.

The MiniBOONE experiment at the Fermilab booster has been approved, and is expected to start taking data in year 2001. Its strategy is to look for a large oscillation signal (about 1000 events in the LSND region) over a large background (about 3000 events, out of which 1700 from beam $\nu_e$, 1200 from misidentification). From the purely statistical point of view the significance of this approach is quite large, but some concern exist on the control of the background ($\pi^0$ production, beam fluxes etc.)

The Lol-216 proposal at CERN is considering the use of the existing low-energy neutrino beam from the PS (old Gargamelle line). Neutrinos are sent to three identical modules, the first acting as a near location at L=130 m and the other two as a far location L=885 m. Each of the three modules will consist of a tracking calorimeter plus a tail- and muon-catcher, for a total mass of $3 \times 130$ tons. The aim is to look for a variation of the $N_e/N_\mu$ ratio between the two locations, in particular a signal is observed if $(N_e/N_\mu)_{FAR} - (N_e/N_\mu)_{CLOSE} > 0$

Using the existing CERN WANF beam, with $<E_\nu> \approx 27$ GeV, a detector placed on the Jura mountains (L=17 Km) would be able to fully explore the LSND region for $\nu_\mu \rightarrow \nu_e$ oscillations. The particularity of this location is that with techniques similar to those already discussed for the
Figure 11: Proposed experiments could fully cover the LSND parameter space for $\nu_\mu \rightarrow \nu_e$ oscillations.

long-baseline case, a $\tau$ search is possible, testing the hypothesis that the LSND effect is instead due to $\nu_\mu \rightarrow \nu_\tau$ oscillations.

A possibility for testing $\nu_\mu \rightarrow \nu_e$ oscillations with almost zero background is to use neutrinos from muon decays instead of the “traditional” beams from pions\textsuperscript{14}. In a storage ring, negative muons would have the following decay $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ producing neutrinos of different flavors and opposite elicity. These neutrinos will interact in a detector producing $\mu^-$ and $e^+$ in case of no oscillation, while in case of $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ or $\nu_\mu \rightarrow \nu_e$ oscillations, leptons of opposite sign are observed. A light detector with charge identification placed at few kilometers from the neutrino production would test the LSND claim after few years of running.

As can be seen in figure 5, these proposals can fully cover the LSND suggested region.

6 Conclusions

Many experimental results in neutrino physics are pointing towards evidence for neutrino oscillation. In particular:

- the results from atmospheric neutrinos need confirmation with different techniques and more precision, i.e. using large detectors
- more information of $\nu_\mu$ disappearance may come from the K2K long-baseline project quite soon; $\tau$ appearance will however only be possible using high-energy long baseline beams
- many experiments are proposed or in preparation to look for $\nu_\mu \rightarrow \nu_e$ oscillations, with a sufficient sensitivity to test the LSND claim

Many experiments, either approved (SuperKamiokande, ICARUS) or proposed (NOE, Aquarich, NICE, OPERA) can play a major role in one or many of the forementioned topics, and neutrino physics promises to be a very hot topic also in the years to come.

Acknowledgments

I would like to thank the conference organizers for having invited me to give this talk. For help in finding information about the different experiments, I thank P.Strolin, P.Migliozzi, P.Picchi, F.Pietropaolo, R.Santacesaria, T.Ypsilantis, L.Ludovici, P.Zucchelli. Many thanks to Andrè Rubbia and Antonio Bueno for useful discussions during the preparation of the talk, and to Cristina Morone for the cover picture.
References

2. P.Cennini et al. ICARUS II Experimental proposal LNGS 94/99-I and 94/99-II
   Rev. Lett. 75, 2650 (1995). Updated results including 1997 data can be found at
10. B. Zeitnitz, KARMEN Collab., proceedings of the Neutrino98 Conference, Takayama, Japan,
    June 1998.
12. CERN/SPSC/97-21, SPSC/1216
13. ICARUS-CERN-Milano Coll., CERN/SPSLC 96-58, SPSLC/P 304, December 1996; J. P.