ICANOE and OPERA experiments at the LNGS/CNGS

André Rubbia

Institut für Teilchenphysik, ETHZ
CH-8093 Zürich, Switzerland

We discuss two experiments ICANOE and OPERA that have been proposed within the context of long-baseline and atmospheric neutrino experiments in Europe. The joint ICANOE/OPERA program aims at further improving our understanding of the effect seen in atmospheric neutrinos. This program is based on (1) a continuation of the observation of atmospheric neutrinos with the improved technique of ICANOE/ICARUS (2) a sensitive $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ appearance program with the accelerator neutrinos coming from CERN (CNGS) from a distance of 730 km.

1. INTRODUCTION

Only a few years ago, neutrinos were believed to be massless. Today a picture is emerging in which three (possibly more) neutrino mass eigenstates exist and mix in different amounts to form the flavor eigenstates relevant to the weak interaction. Each year brings its load of new information on neutrinos. But a complete neutrino pattern is still missing. Several new experiments will further fill in the neutrino pattern, the final goal being the comprehensive elucidation of the neutrino masses and mixings. This goal will necessarily be remembered as a fundamental milestone in particle physics, astrophysics and cosmology.

Focusing on experiments detecting neutrinos produced in the Earth atmosphere, the data consistently show

1. Only muon "disappearance" has so far been observed; convincing signal for flavor oscillation is the detection of an "appearance" effect; the presence of matter effects disfavors transitions to sterile neutrinos[1]; since maximal $\nu_\mu \rightarrow \nu_e$ is excluded by current data[4], this means detecting $\nu_\mu \rightarrow \nu_\tau$ appearance.

2. Given the tau threshold, tau appearance is most easily performed with high energy neutrinos produced at accelerators.

3. Evidence for $\nu_\mu \rightarrow \nu_\tau$ appearance in the atmospheric data should also be attempted;

the path length between the source and the detector and $E$ the neutrino energy. The energy of the involved neutrinos and the reconstructed path lengths between production points and detectors can be fitted assuming the disappearance expression of Eq. (1) to extract $\Delta m^2$ and the mixing amplitude. The most stringent constraint comes from SuperK which yields the following 90% C.L. region[1]:

$$\Delta m^2 \approx (2 - 6) \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta \approx 0.8 - 1$$

While current data are extremely convincing, in particular that of SuperK, there is a certain number of new measurements that can further improve our understanding of the atmospheric neutrino effect:

1. Only muon “disappearance” has so far been observed; convincing signal for flavor oscillation is the detection of an “appearance” effect; the presence of matter effects disfavors transitions to sterile neutrinos[1]; since maximal $\nu_\mu \rightarrow \nu_e$ is excluded by current data[4], this means detecting $\nu_\mu \rightarrow \nu_\tau$ appearance.

2. Given the tau threshold, tau appearance is most easily performed with high energy neutrinos produced at accelerators.

3. Evidence for $\nu_\mu \rightarrow \nu_\tau$ appearance in the atmospheric data should also be attempted;
this requires large exposures to accumulate enough events at sufficiently high energy, good event reconstruction at high energy and good detector granularity to separate tau decays from backgrounds.

4. The predicted $L/E$ dependence of the flavor oscillation has so far been observed with rather poor resolution; in particular, other models of disappearance with “exotic” decays cannot be completely excluded\cite{5}; a convincing signal is the observation of at least a full $L/E$ “oscillation” which requires sufficient $L/E$ “range” and resolution.

In addition, most of the current analyses have been performed within the so-called “two-family” mixing scenario. Since we know with certainty that three flavor eigenstates exist, we should at least consider the mixing with three mass eigenstates $m_1$, $m_2$ and $m_3$. For the case of atmospheric region, this opens the interesting possibility that oscillations involving tau-type and electron-type take place simultaneously, though with different probabilities. Current best constraints come from reactor experiments reported by Gratta\cite{4}, which limit the element of mixture between electron-type neutrino and $m_3$ to a mere $\sin^2 \theta_{13} < \approx 0.1$. One would clearly like to improve this result.

2. PROPOSED PROGRAM AT LNGS

Two experiments have been proposed within the context of long-baseline and atmospheric neutrino experiments at CERN: ICANOE\cite{6} and OPERA\cite{7}. A third experiment, MONOLITH, has also been proposed and discussed by Geiser\cite{8}.

The joint ICANOE and OPERA program aims at contributing to the questions described in the introduction. It is really based on these points:

1. a continuation of the observation of atmospheric neutrinos with the improved technique of ICANOE/ICARUS;

2. a sensitive $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ appearance program with the accelerator neutrinos coming from CERN (CNGS) from a distance of 730 km.

In addition, ICANOE is sensitive to proton decays in the lifetime range of $> 10^{33}$ years. While this sensitivity is not sufficient to explore convincingly proton decay, ICANOE will be the test-bed to confirm that absolutely background-free searches can be achieved thanks to the excellent imaging of the detector. Hence, ICANOE could open the road to more massive detectors (in the range of 30 kt) capable of exploring proton decay in the range of $> 10^{44}$ years\cite{9}.

The two proposals, while technologically challenging compared to “traditional” massive neutrino detectors, are both based on many years of R&D undertaken in Europe. They can be considered as natural follow-ups of the NOMAD and CHORUS experiments performed at CERN between 1994 and 1998.

The CERN council has so far only approved in December 1999 the construction of the CNGS beam. The two experiments have not yet been approved, but progress is expected within a short time, since the current schedule foresees the commissioning of the CNGS beam in the year 2005. It is currently planned that experiments should have access to the LNGS hall already in the year 2002 in order to be ready for 2005.

Clearly, the part of the program dedicated to atmospheric neutrinos should start as soon as possible.

3. ICARUS/ICANOE

The ICARUS technology provides an excellent general purpose large scale neutrino detector: it offers within the same volume a tracker in three dimensions with high spatial resolution and particle identification, and also, because of the high density of the liquid medium, precise homogeneous calorimetry.

This detector technology combines the characteristics of a bubble chamber with the advantages of the electronic read-out. The $LAr$ TPC is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of
fine pitched wire grids), it is possible to obtain a massive “electronic bubble chamber” with superb 3D imaging.

The characteristics are the following: (a) it has excellent imaging capabilities, i.e. a “bubble-chamber” like device; (b) the target is fully isotropic and homogeneous; (c) it is a tracking device, capable of dE/dx measurement. The high dE/dx resolution allows both good momentum measurement and particle identification for soft particles; (d) electromagnetic and hadronic showers are fully sampled. This allows to have a good energy resolution for both electromagnetic, \( \sigma(E)/E \approx 3\%/\sqrt{E/\text{GeV}} \); and hadronic contained showers, \( \sigma(E)/E \approx 15\%/\sqrt{E/\text{GeV}} \); (e) It has excellent electron identification and \( e/\pi^0 \) discrimination thanks to the ability to distinguish single and double m.i.p. by ionization and to the bubble chamber quality space resolution; (f) calorimetry allows full kinematics reconstruction of “contained” events; (g) muon momentum can be determined by multiple scattering \( \Delta p/p \approx 20\% \) for long tracks; (h) it is continuously sensitive, self-triggerable, cost effective and simple to build in modular form, sufficiently safe to be located underground.

The ICARUS technique was studied and demonstrated by an extensive R&D program which included ten years of studies on small volumes (proof of principle, purification methods, readout schemes, mixtures of argon-methane, diffusion coefficients, electronics) and five years of studies with several detectors at CERN (purification technology, real events, pattern recognition, event simulations, long duration tests, doping, readout technology). The largest of these devices has a mass of 3 tons. A 50 liters prototype has been exposed to the CERN neutrino and recently tracks with electron drift paths of about \( \approx 140 \) cm have been obtained[10].

With the cooperation of specialized industries, it is now conceivable to build very large scale devices. AirLiquide has been chosen for the construction of the large cryostat and for the Argon purification system. BREME Tecnica has been selected for the internal detector mechanics. CAEN will produce the readout electronics in large scales. After several years of intense R&D and prototyping, the ICARUS Collaboration is now realizing the first 600 ton module, which will be installed at the Gran Sasso Laboratory in the year 2001.

A recent major step in the R&D program has been the construction and operation of a fully industrial module of 15 ton (T15 prototype). This device has provided (a) a full-scale test of the cryostat technology; (b) a test of the “variable geometry” wire chambers; (c) a test of the liquid phase purification system; (d) a test of the liquid phase purification system; (e) a test of the liquid phase purification system; (f) a test of the liquid phase purification system; (g) a test of the liquid phase purification system; (h) a test of the liquid phase purification system. This test can be considered as the first operation of a 15 ton LAr mass as an actual “detector”. More details can be found in Ref.[11].

### Table 1
Predicted performance of the new CNGS reference beam for an isoscalar target.

| Process | Rates (events/kton/year) |
|---------|-------------------------|
| \( \nu_\mu \) CC |
| \( \bar{\nu}_\mu \) CC |
| \( \nu_e \) CC |
| \( \bar{\nu}_e \) CC |
| \( \nu \) NC |
| \( \bar{\nu} \) NC |

### 4. OPERA

OPERA[7] is the design of a massive detector able to operate on a medium or long baseline location, to explore \( \nu_\mu - \nu_\tau \) oscillations based on the emulsion technique. In OPERA, emulsions are used as high precision trackers, unlike in CHORUS where they compose the active target. The extremely high space resolution of the emulsion should cope with the peculiar signature of the short lived \( \tau \) lepton, produced in the interactions of the \( \nu_\tau \). Since the emulsion does not have time resolution, there are electronic detectors after each module in order to correlate the neutrino interactions to the brick where they occur and to guide the scanning.

### 5. PHYSICS WITH THE CERN BEAM
Table 2
Expected number of $\nu_\tau$ CC events at Gran Sasso per kton per year for an isoscalar target. Results of simulations for different values of $\Delta m^2$ and for $\sin^2(2\theta) = 1$ are given for $4.5 \times 10^{19}$ pot/year. These event numbers do not take detector efficiencies into account.

| Energy region $E_{\nu_\tau}$ (GeV) | 1-30 | 1-100 |
|-------------------------------------|------|-------|
| $\Delta m^2 = 1 \times 10^{-3}$ eV$^2$ | 2.34 | 2.48 |
| $\Delta m^2 = 3 \times 10^{-3}$ eV$^2$ | 20.7 | 21.4 |
| $\Delta m^2 = 5 \times 10^{-3}$ eV$^2$ | 55.9 | 57.7 |
| $\Delta m^2 = 1 \times 10^{-2}$ eV$^2$ | 195  | 202  |

Table 3
Fully identified tau events from $\nu_\mu \rightarrow \nu_\tau$ oscillations and background. Rates normalized to 4 years “shared” running of CNGS ($4 \times 4.5 \times 10^{19}$ pots).

| $\Delta m^2$ (eV$^2$) | ICANOE | OPERA |
|-----------------------|--------|-------|
| $2 \times 10^{-3}$    | 12     | 4.6   |
| $3 \times 10^{-3}$    | 26     | 10.5  |
| $3.5 \times 10^{-3}$  | 35     | 14.3  |
| $5 \times 10^{-3}$    | 71     | 29    |
| $7 \times 10^{-3}$    | 121    | 57    |
| $10 \times 10^{-3}$   | 248    | 117   |
| Background            | 5.1    | 0.43  |

5.1. The CNGS beam
The general strategy was to opt for a wide band neutrino beam based on the experience gathered at CERN with the design and the operation of the WANF.

The primary proton have 400 GeV and assuming 200 days per year at peak intensity $4.8 \times 10^{13}$ per cycle, with 55% overall efficiency, one expects $4.5 \times 10^{19}$ pot/year. In dedicated mode, up to $7.6 \times 10^{19}$ pot/year could be achieved.

The expected event rates per kton and year in shared mode are listed in Table 2.

A first optimization of the beam has been carried out with the goal of maximizing the $\nu_\tau$ CC interactions at LNGS for appearance experiments. The optimization of the tau event rates introduces conflicting requirements. Indeed, given the fixed baseline of 730 km and the wish to optimize the rate in the region $\Delta m^2 \approx 10^{-3} - 10^{-2}$ eV$^2$, the probability of oscillation scales like $1/E^2$. But the tau kinematical suppression requires high energy. This rate has been optimized by adjusting the focusing system of the beam and the following rates for tau appearance with maximal mixing $\sin^2(2\theta) = 1$ in shared running mode are obtained in Table 3.

5.2. $\nu_\mu \rightarrow \nu_\tau$ appearance
It should be stressed that for most of the $\Delta m^2$ region allowed by Superkamiokande, the rate of $\nu_\tau$ CC events is so high as to give a statistical excess even prior or with mild selection cuts. This is one of the main reason to perform this experiment at long baseline!

In the case of ICANOE, the expected number of $\nu_\tau$ CC with $\tau \rightarrow e\nu\nu$ before any selection cuts for $\Delta m^2 = 3.5 \times 10^{-3}$ eV$^2$ is $\simeq 110$
events in four years of “shared” running, while the background from $\nu_e, \bar{\nu}_e$ CC amounts to about 470 events. Such an excess can be seen prior to kinematical cuts, for example in the visible energy distribution of events as shown in Figure 1. The actual cuts will therefore be imposed a posteriori in order to optimize the sensitivity for a given $\Delta m^2$.

Because of the high resolution on measuring kinematical quantities, the $\nu_e$ appearance search is based on the kinematical suppression of the background using similar techniques to those of the NOMAD experiment. The electron channel in the liquid Argon provides a golden sample. The leading electron is identified and precisely measured. To reconstruct the hadronic jet, the detector is used as an homogeneous calorimeter. The main background of the intrinsic $\nu_e$ CC component of the beam is suppressed to a few events, while keeping a $\approx 30\%$ efficiency for the signal.

In OPERA, the $\tau$’s produced in $\nu_\tau$ CC interactions, are detected by measuring their decay kink. Current estimates of the number of background events expected yield values below 1 in four years. Thus OPERA is believed to be essentially free of backgrounds.

The number of fully identified tau events from $\nu_\mu \rightarrow \nu_\tau$ oscillations as a function of $\Delta m^2$ and for maximal mixing, and the remaining background after selection cuts for ICANOEU and OPERA are listed in Table 8. These excellent performances justify the label “direct tau appearance searches”.

5.3. $\nu_\mu \rightarrow \nu_e$ appearance in three family mixing

We note that for three neutrinos, the three squared mass differences $\Delta m^2_{12}$, $\Delta m^2_{13}$ and $\Delta m^2_{23}$ are linearly dependent, so one has only two free squared mass difference scales. The standard assignment is as such: the smallest one (say $\Delta m^2_{12}$) is attributed to the solar neutrino deficit and $\Delta m^2_{23} \approx \Delta m^2_{13}$ is set at the atmospheric neutrino anomaly scale.

In the “standard” parameterization of the mixing matrix analogous to the CKM matrix in the quark sector, the amount of $\nu_e \rightarrow \nu_\mu$ oscillations is determined by the mixing angle known as $\theta_{13}$. Indeed, one has:

\[
P(\nu_e \rightarrow \nu_\mu) = \frac{1 - \sin^2(2\theta_{13})\Delta m^2_{32}}{1 + \sin^2(2\theta_{13})\Delta m^2_{32}}
\]

(4)
columns list the contribution from $\nu_e$ CC (intrinsic beam contamination), the amount of $\nu_\tau$ CC with electron decay of the tau for $\Delta m^2 = 3.5 \times 10^{-3}$ eV$^2$ and maximal mixing, and the amount of $\nu_\mu \to \nu_e$ oscillated events. The last column shows the statistical significance of the $\nu_\mu \to \nu_e$ excess. Hence, ICANOE will test the $\theta_{13}$ angle down to a few degrees.

6. ATMOSPHERIC NEUTRINOS

ICANOE can give fundamental contributions to the study of atmospheric neutrinos in different aspects, thanks to its unique performances in terms of resolution and precision. In order to achieve a better understanding of neutrino phenomenology, it is fundamental to have coherent results from different kind of measurements, showing that all of them can be interpreted within an unique model. Therefore, the possibility of measuring atmospheric neutrinos with the same detector operating in the long-baseline beam is considered a fundamental feature in order to establish a robust confidence on the results. The perspective, as far as atmospheric neutrinos are concerned, is to provide redundant, high precision measurement and minimize as much as possible the systematics uncertainties of experimental origin which affect the results of existing experiments. Improvements over existing methods are expected in

1. neutrino event selection
2. identification of $\nu_\mu$, $\nu_e$ and $\nu_\tau$ flavors
3. identification of neutral currents

To illustrate the physics reach, we consider the so-called $L/E$ analysis. In order to verify that atmospheric neutrino disappearance is really due to neutrino oscillations, an effective method consists in observing the modulation given by the characteristic oscillation probability of Eq. 1. This modulation will be characteristic of a given $\Delta m^2$, when the event rate is plotted as a function of the reconstructed $L/E$ of the events when compared to theoretical predictions. The ratio of the observed and predicted spectra has the advantage of being quite insensitive to the precise knowledge of the atmospheric neutrino flux, since the oscillation pattern is found by dips in the $L/E$ distribution while the neutrino interaction spectrum is known to be a slowly varying function of $L/E$. Such a method is in principle capable of measuring $\Delta m^2$ exploiting atmospheric neutrino events. A smearing of the modulation is introduced by the finite $L/E$ resolution of the detection method. Precise measurements of energy and direction of both the muon and hadrons are therefore needed in order to reconstruct precisely the neutrino $L/E$. Figure 2 shows the survival probabilities as a function of $L/E$ ratio for oscillation (triangles) and decay hypothesis (circles). Only statistical error has been considered.

Figure 2. Survival probability as a function of the $L/E$ ratio for oscillation (triangles) and decay hypothesis (circles). Only statistical error has been considered.

More details can be found in Ref. [6]. In particular, tau appearance in the atmospheric “beam” is very attractive. Statistically significant signals require exposures of more than 20 kt $\times$ years, but still are achievable in 4-5 years running.
Finally, ICANOE can also measure upward-going muons from neutrinos interacting in the surrounding rock. In fact, the design and size of ICANOE are such to make it also a large area detector.

7. NUCLEON DECAY

Nucleon decay is likely to occur at some level; if experimentally observed it can be used to determine fundamental properties of the nature and the structure of the Unifying Gauge Theory at a scale of $10^{-32}$ cm. From the experimental point of view, the challenge matches the importance of the issue.

Future nuclear decay experiments have to be able to combine a large mass, the capability of distinguishing between several possible decay channels and a good background discrimination, in order to increase their sensitivity linearly with the mass.

As a specific example of the capabilities of ICANOE, Figure 3 shows a simulated proton decay in the mode $p \rightarrow \nu K^+$. This is one of the favored SUSY decays, and is quite typical due to the presence of a strange meson in the final state. A liquid Argon detector can profit from its very good particle identification capabilities to tag the kaon and its decay products. We recall here that the kaon is typically below the Cerenkov threshold for water, therefore it can be seen in a large water detector only via its decay products.

Background-free searches can be performed given the excellent imaging of the detector. Single events will provide evidence for signal. More details can be found in Refs. [3][4].

ACKNOWLEDGMENTS

I thank A. Ereditato for material on OPERA. The help of A. Bueno and J. Rico in preparing this talk is greatly acknowledged. I also thank the organizers of the Neutrino-2000 conference.

REFERENCES

1. H. Sobel, (Super-Kamiokande Collab.), these proceedings.

2. A. Mann, (Soudan-2 Collab.), these proceedings.

3. B. Barish, (MACRO Collab.), these proceedings.

4. see e.g. G. Gratta, (Palo-Verde Collab.), these proceedings.

5. V. Barger, J. G. Learned, P. Lipari, M. Lusignoli, S. Pakvasa and T. J. Weiler, Phys. Lett. B462 (1999) 109 [hep-ph/9907421].

6. F. Arneodo et al. [ICARUS and NOE Collab.], “ICANOE: Imaging and calorimetric neutrino oscillation experiment,” LNGS-P21/99, INFN/AE-99-17, CERN/SPSC 99-25, SPSC/P314; see also A. Rubbia [ICARUS collaboration], hep-ex/0001052. Updated information can be found at http://pcnometh4.cern.ch.

7. M. Guler et al. [OPERA Collaboration], CERN/SPSC 2000-028, SPSC/P318, LNGS P25/2000

8. A. Geiser, (MONOLITH Collab.), these proceedings.

9. A. Bueno for ICARUS Collab., presented at NNN00 Fermilab Nucleon Decay and Neutrino Detector workshop, FNAL, August 2000.
10. F. Arneodo et al., Nucl. Instrum. Meth. A449 (2000) 36.
11. F. Arneodo for the ICARUS Collab., “Frontier Detectors For Frontier Physics”, May 2000.