EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–PPE/95–133
29 August 1995

THE CERN–GRAN SASSO LONG-BASELINE NEUTRINO-BEAM PROJECT

Flavio Cavanna

Dept. of Physics, University of Aquila and INFN-Laboratori Nazionali del Gran Sasso, Italy

Abstract

A remarkable effort is at present under way to prepare a new generation of neutrino experiments to clarify definitively the intriguing 'puzzle' of neutrino oscillations. In particular, one interesting possibility to increase the sensitivity of accelerator neutrino experiments, down to the regions indicated by the atmospheric neutrino data (small Δm^2), is to extend the baseline outside the limits of the laboratory. Thus, long-baseline experiments represent a complementary approach to the present short-baseline experiments which are studying small $\sin^2 2\theta$ values. Long-baseline neutrino-beam projects are under discussion or being approved in various High-Energy Physics Laboratories in the world. Today, the CERN–Gran Sasso beam project is around generating increasing interest in the European physics community and some experiments have been proposed to use this facility at the Gran Sasso Laboratory. A preliminary design of the CERN neutrino-beam set-up and calculations of the beam properties at Gran Sasso site have been performed with detailed Monte Carlo simulations. We report here a review of the results from these studies together with the main aspects of the technical solutions and of the physical capabilities of the proposed experiments.

Presented at the 9èmes Rencontres de Physique de la Vallée d'Aoste – Results and Perspectives in Particle Physics, La Thuile, Italy, 5–11 March 1995

1 NEUTRINO OSCILLATIONS WITH LONG-BASELINE BEAMS

Neutrino physics represents a new frontier in particle physics, a necessary complement to the High-Energy Frontier with the $\mathrm{p\bar{p}}$ Collider at FNAL and the Large Hadron Collider (LHC) at CERN and to the High-Precision Frontier with the LEP, the SLC, and the $\Phi, \mathrm{b}, \mathrm{K}$ and charm-τ factories.

In the Standard Model, neutrinos are massless but without compelling reasons. Reasons implying new physics beyond the Standard Model, which could explain some of its arbitrary features, lead us to postulate that neutrinos have a non-zero rest mass.

Massive neutrinos occur naturally in Grand Unified Theories (GUTs). In particular, the 'see-saw' mechanisms provide a direct connection between the unification of forces and the nature of the neutrino masses. Moreover, massive neutrinos play a fundamental role in cosmology, being a prime candidate as a dark matter constituent. Therefore, the neutrino sector illustrates well the complementarity between particle physics and nuclear astrophysics and cosmology.

However, no definite theoretical guidance for the neutrino mass is available. This means that if the neutrino has non-zero mass, then the question arises, is it a pure eigenstate of weak interaction or is it a superposition of eigenstates of the mass matrix? If the neutrino is a mixed state in this sense, the so-called neutrino oscillation phenomenon may take place, with lepton number violation. As a consequence, the counting rate in a detector placed at varying distances from the neutrino source will vary periodically with the distance. This is shown by the well-known formula for the probability of oscillation between two neutrino flavours ($\alpha,\ \beta = \mathrm{e}, \mu, \tau$):

$$P(\nu_\alpha \leftrightarrow \nu_\beta) = \sin^2 2\theta_{(1,2)} \times \sin^2(1.27\ \Delta m^2_{(1,2)}\ \frac{L}{E}) \tag{1}$$

where $\theta_{(1,2)}$ is the mixing angle and $\Delta m^2_{(1,2)}$ is the squared mass difference between two neutrino mass eigenstates $(1,2)$; E and L are, respectively, the neutrino energy and the distance.

Thus, the experimental observation of neutrino oscillations ($P(\nu_\alpha \leftrightarrow \nu_\beta) \neq 0$) provides direct indications of the non-zero neutrino mass and mixing.

Detailed experimental studies of neutrino oscillations have been carried out with the help of nuclear reactors, providing low-energy neutrinos, and of accelerators, providing high-energy neutrino beams. In both cases, the results obtained so far have not revealed any clear evidence[1] for neutrino oscillations. Among the oscillation channels explored were $\nu_\mu \to \nu_\mathrm{e}$, $\nu_\mu \to \nu_\tau$, and $\nu_\mu \to \nu_x$. The parameter spaces excluded so far in the $\nu_\mu \to \nu_\mathrm{e}$ and $\nu_\mu \to \nu_\tau$ channels are summarized in Section 2.2.

On the other hand, the possible existence of neutrino oscillation has recently received some experimental support, both from the observation of a deficit of solar neutrinos and from the apparent ν_μ/ν_e anomaly in the interactions of atmospheric neutrinos observed by large underground detectors. In Section 2.2 the allowed regions in the oscillation parameter space are also reported.

The next step in the study of neutrino oscillations will rely on improved or new detector technologies and on larger sensitive mass.

In particular, one interesting possibility to increase the sensitivity of accelerator neutrino experiments, down to the regions indicated by the atmospheric neutrino data (small Δm^2), is to extend the baseline (L) outside the typical limits (hundreds of metres) of the HEP laboratories. In fact, from Eq. (1), for a given neutrino-beam energy the sensitivity to Δm^2 depends on $1/\sqrt{L}$ as soon as one considers the oscillation signal $N_\mathrm{s}(\nu_\beta)$ in the presence of the irreducible background

---

[1] A recent search [1] for $\bar{\nu}_\mu \to \bar{\nu}_\mathrm{e}$ oscillations with a beam stop experiment at LAMPF finds an excess of $\bar{\nu}_\mathrm{e}$ events with respect to the expected background from conventional processes. However, this result needs to be confirmed.

N_b. Therefore to explore small Δm^2 regions it is desirable to extend the baseline as much as possible.

Thus, a long-baseline experiment represents a complementary approach to the present short-baseline experiments which are studying small $\sin^2 2\theta$ values.

Long-baseline neutrino-beam projects are under discussion at CERN, Fermilab, Brookhaven, KEK and Serpukhov. Large target mass detectors located at far distance (hundreds of kilometres) are planned or currently under construction at the Gran Sasso Laboratory, the NESTOR Underwater Laboratory, the Soudan site and Kamioka.

The CERN–Gran Sasso beam project and an updated overview of the proposed experiments to use this facility are the subjects of this paper.

2 THE CERN–GRAN SASSO PROJECT

As part of the work for the CERN LHC project, injection transfer lines are being designed to bring fast extracted proton beams from the SPS to the LHC. Considering the planned SPS–LHC proton transfer line TL87 (from the SPS/LSS4 to LHC/P8), a feasibility study [2] has shown that it is technically possible to derive a neutrino beam pointing to Gran Sasso 732 km away in Italy (Fig. 1), which happens to be in a favourable azimuthal direction with respect to this line. The geometry of TL87 is not completely defined yet. It could be made of two arcs separated by a straight section, equipped with superconducting magnets, or a single long arc, equipped with classical warm magnets. In both cases a primary proton beam can be fast-extracted from the SPS and branched off to the neutrino production zone in the upstream part of the transfer line [3]. In the first scheme only minor vertical and horizontal deflections are needed to extract and direct the protons onto the target, towards the Gran Sasso Laboratory, whereas in the second scheme a dedicated extra tunnel has to be excavated towards the neutrino target in the Gran Sasso direction. In any case, part of the overhead in the civil engineering would already be accounted for in the LHC project [4].

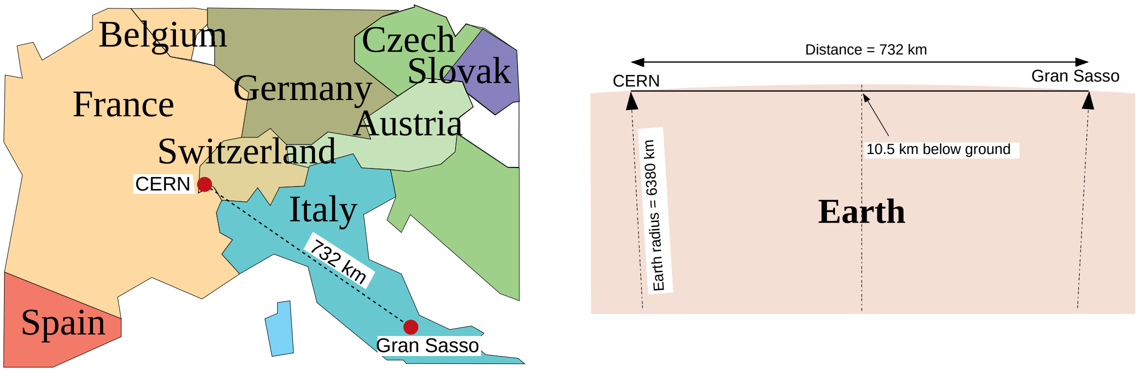

Figure 1: (a) Geographic configuration of the planned neutrino beam from CERN to Gran Sasso and (b) cross-sectional view of the Earth showing the path of the neutrino beam

At the end of the target/focusing-system station (20–25 metre length) a decay tunnel has to be excavated, pointing to the Gran Sasso Laboratory with high precision. The slope with respect to the horizontal plane is of 3.283° downwards. A schematic beam layout is shown in Fig. 2. The question of the need for a ‘near detector’ has still to be addressed. From a preliminary study, the excavation of a hall, at the end of the decay tunnel, for housing a monitor detector seems to be technically feasible but the engineering and the cost have not been estimated yet. A detailed study of the real benefit of such a facility has to be performed first.

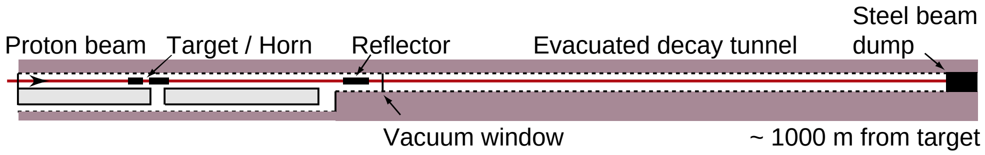

Figure 2: General layout of the CERN neutrino beam line for Gran Sasso

2.1 The CERN neutrino beam and the event rate at Gran Sasso

Proton accelerators provide essentially ν_μ beams from the decay of π's and K's, produced when the extracted proton beam hits a target. These 'parent' particles are focused towards the detector and left to decay in a long tunnel to produce muons and ν_μ's. The muons and all remaining hadrons are dumped at the end of the decay tunnel leaving only the neutrinos travelling towards the detector target. Recently two independent studies [5], [6], based on detailed Monte Carlo simulations, have been performed to define possible geometries for a CERN neutrino beam set-up and to calculate the corresponding beam fluxes, beam contaminations, and the resulting event rates at different far detector sites.

In both studies the neutrino production target is assumed to be of the same type as that currently in use for the short-baseline experiments at CERN. It consists of a string of beryllium rods, 3 mm in diameter and 1.2 m total length. Compared with targets of different geometry and materials this solution provides optimum efficiency, i.e. highest flux of neutrinos per primary proton. The use of this type of target at present requires that the proton intensity be kept at $< 1.5\times 10^{13}$ pot/FE (protons on target per Fast Extraction) to handle safely the large heat load dissipation of the target. New technical solutions are under study to allow higher proton-beam intensity on target.

A number of possibilities have been investigated to focus the secondary beam after the target. Among these, systems of co-axial magnetic lenses (a horns-and-reflectors system in Ref. [5] or a simple horn in Ref. [6]) are preferred as they provide a broader energy and angular acceptance, hence higher neutrino flux, are sign-selective, and are known to be radiation-hard and to operate with high reliability. Moreover, assuming a given primary proton energy, then by operating on the focusing system the neutrino mean energy can be varied to a certain extent.

After the focusing station a decay pipe of 1.5 m radius and total length from the target of $800 \div 1000$ m has been assumed in both the present calculations. As shown in Ref. [5], a longer decay length has the advantage of increasing the neutrino flux (ν_μ), see Fig. 3a, but increases the high-energy component and seems to enrich the ν_{e} contamination from muon decay. The pipe diameter has been optimized to contain almost all the secondary particles whose decays produce the neutrinos interacting within the geometrical acceptance of the far detector, see Fig. 3b.

The characteristics of the resulting neutrino beam can be calculated as soon as the primary proton energy and intensity are defined.

The beam simulation studies have definitively shown that, assuming a fixed proton intensity, the highest proton energy is preferable if one wants to maximize the number of events in the detector. This is shown in Fig. 4 from Ref. [6] where the energy and the transverse momentum distributions of secondary K's and π's from proton interactions on target at different energies (450 GeV and 80 GeV) are compared. The production of secondary particles (and the corresponding neutrino flux) is larger at all energies when the proton energy is higher, but the shape of the p_{T} distribution (and the corresponding neutrino beam divergency) is practically independent from the primary energy. Therefore, for a given proton intensity, the expected rate of neutrino interactions at the far detector site is maximum when the highest proton beam energy is assumed.

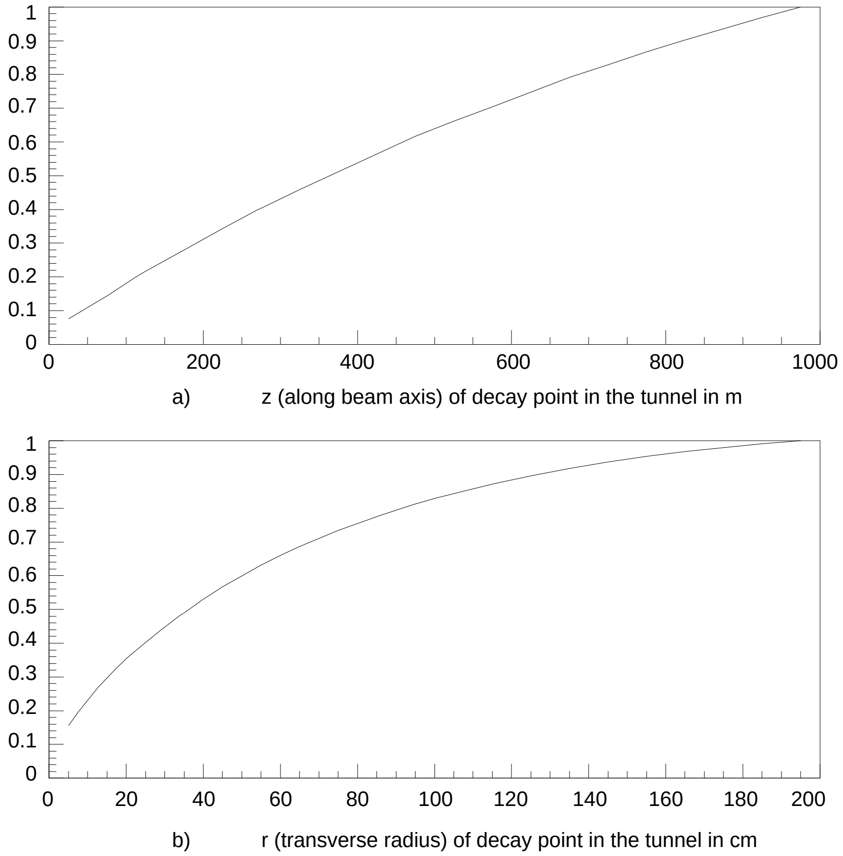

Figure 3: (a) Cumulative z distribution and (b) cumulative radial distance distribution for events inside the fiducial area of the detector at Gran Sasso. Both distributions are from Ref. [5]

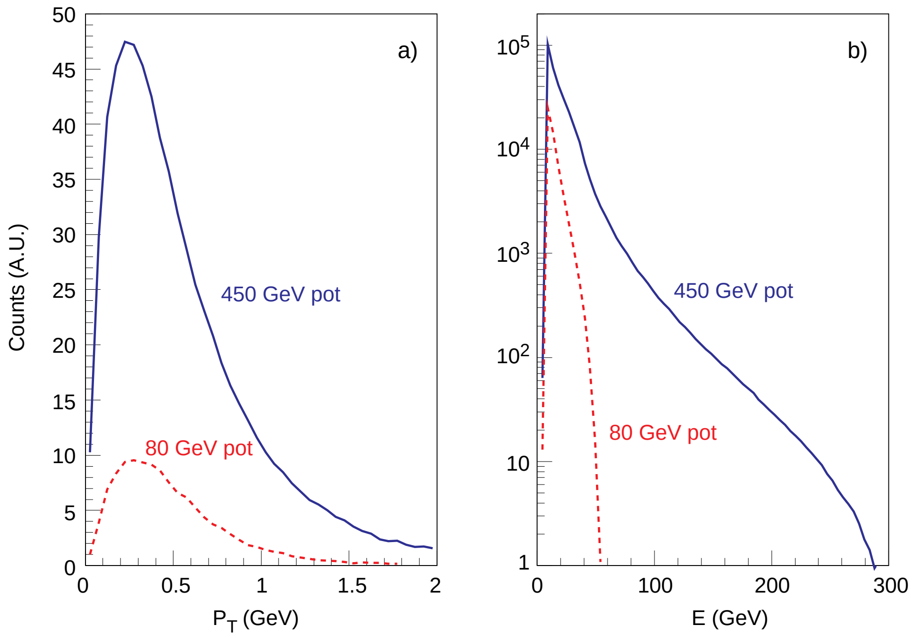

Figure 4: (a) p_{T} distribution and (b) energy distribution of secondary K's and π's from proton interactions on a beryllium target

The SPS machine aspects (cycling time, extraction structure, intensity, target capacity) for a long-baseline neutrino-beam design have been only preliminarily studied [7] and more work on the optimization of the beam is necessary. We report here some considerations based only on the currently available technologies and experience.

The normal SPS cycle at $450\ \mathrm{GeV}/c$ has a period of 14.4 s with a proton intensity of 3.8×10^{13} pot/cycle. In the usual shared mode of operation with two fast extractions (from LSS4) of $1 \div 1.3 \times 10^{13}$ pot/FE, and assuming one operating year of 10^7 s with 70% efficiency, the SPS would deliver about 1×10^{19} protons onto the neutrino production target. With an appropriate machine development, it could be envisaged to shorten the SPS cycle to 7.2 s which would mean that up to 2×10^{19} protons per year could be supplied to the neutrino target. However, in this case the operation of the SPS would be dedicated to the long-baseline experiment only. A time window for such a dedicated mode could be after the end of the LEP operations and before the LHC start-up, i.e. in the years 2000–2004. Recent evaluations [7] show that running the SPS just below the maximum energy (i.e. at $400\ \mathrm{GeV}/c$) could allow a significant increase of the number of protons on target, up to 3×10^{19} pot/year in dedicated mode.

At this stage the beam calculations refer to a primary proton energy of $450\ \mathrm{GeV}/c$ and to a reference number of 1×10^{19} pot/year.

The essential part of the information is the expected ν_μ flux and ν_e contamination (from kaon and secondary muon decay) at the far sites. These were calculated in both studies [5] and [6] by Monte Carlo simulations with a detailed GEANT [8] description of the beam set-up. The major systematic uncertainty in estimating neutrino fluxes is the model of hadronic interactions used to obtain the production spectra. Different production models have been compared in Ref. [5]. Among these, a recent version of FLUKA [9] is thought to reproduce better the energy part of interest of the production spectrum. However, the uncertainty in quoted fluxes and event rates must be at present considered of the order of 20%, mainly due to the lack of experimental data on particle production at energies well below that of the incident beam.

The neutrino fluxes (for ν_μ and ν_e) were calculated with different methods in Refs. [5] and [6], although the GEANT+FLUKA framework was used in both studies. In the first case the products of the hadronic interactions are tracked through the optical system, focused, and then allowed to decay. Secondary interactions, absorption and multiple scattering in all materials were included. The neutrinos from the decays occurring within the decay tunnel are projected to the surface of the detector located at Gran Sasso. The event rate is finally calculated convoluting the neutrino fluxes with the relative interaction cross-sections. The main limitation of this method is statistical: the extremely small solid angle defined by the far detector surface selects only a minimal fraction of the generated neutrino sample, requiring therefore a large CPU time consumption. This simulation has been used also to calculate fluxes and event rates at the NESTOR Underwater Laboratory(2) in the Ionian Sea [10]. The second method allows one to obtain simulations at high statistics by limiting the use of GEANT+FLUKA to the production of secondary particles from hadron interactions within the target. To each secondary particle exiting the target one associates its global probability of decaying within the decay tunnel dimensions, giving a ν_μ (ν_e) emitted in the forward direction and subsequently interacting in the detector. As a test, the same simulation algorithm was applied to the present CERN short-baseline beam configuration: event rates and background rates were predicted correctly within $< 10\%$.

---

(2) A feasibility study has shown that is also possible to send a neutrino beam from CERN, extracting protons from the same SPS to LHC transfer line, to the NESTOR Underwater Laboratory, 1676 km away in the Ionian Sea. However, it will require a separate beam layout (target/focusing station and decay tunnel) from the beam to Gran Sasso.

The results of the two calculations cannot be compared directly since the different optical systems in use introduce large variations in the expected mean neutrino energy at the far detector. Therefore, to check the compatibility of the two methods, the notion of so-called ‘perfect focusing’ has been introduced: in the perfect-focusing scheme the hadronic secondaries are forced, by means of an ideal optics, to be propagated along directions parallel to the axis of the decay tunnel. A very good agreement has been found, comparing the results of the two beam calculations with perfect focusing, in terms of total flux and ν_e contamination at the Gran Sasso site. We can take this as an important confirmation that the calculations are reliable and considerations on possible detector design can be safely based on them.

Table 1: The Gran Sasso event rates per kton with different geometries of the focusing system, using a 450 GeV/c primary proton beam and normalized to 10^{19} protons on target. Data in the last row corresponds to the full line distributions in Fig. 5.

Geometry	Events/10^{19}pot/kton	$< E_\nu^{-2} >^{-1/2}$ (GeV)	ν_e/ν_μ (%)
H20R40 [5]	473	10.5	1.4
H40R70 [5]	722	14.2	1.1
Single horn [6]	1040	22.8	0.65

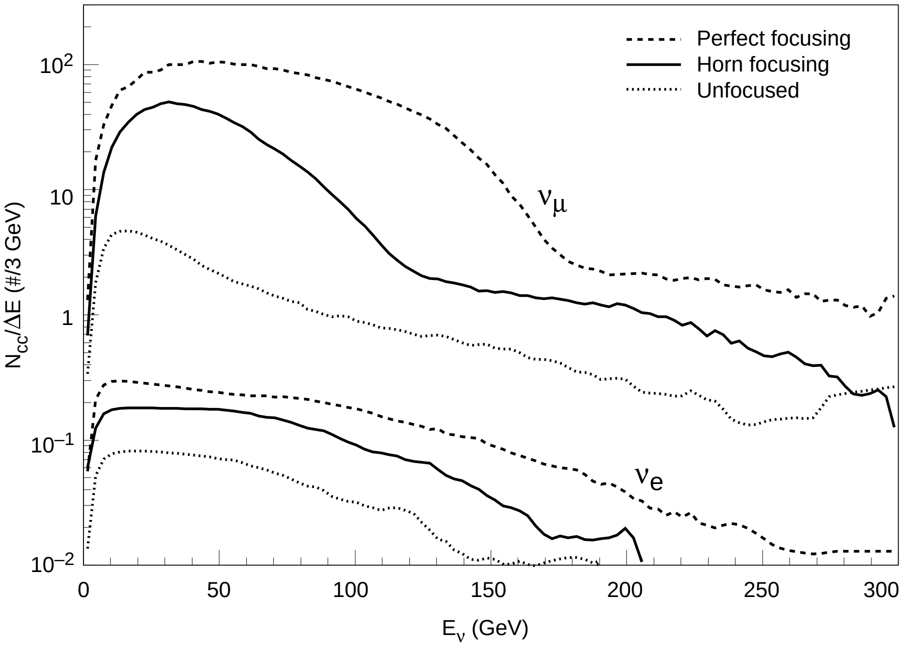

Figure 5: Energy spectrum of the CC neutrino interactions from Ref. [6]. The vertical axis corresponds to the number of ν_μ or ν_e CC events per 3 GeV bin of incident energy, occurring in 1 kton of detector mass at Gran Sasso, with the CERN SPS delivering 1×10^{19} protons on target at an energy of 450 GeV.

The main results from the two simulations with the realistic focusing, are reported in Table 1. The event rates per kiloton are normalized to 10^{19} protons on target. The larger event rate of Ref. [6] is due to the higher mean neutrino energy from the single-horn optics and to the linear behaviour of the neutrino cross-section. The expected [6] energy distributions of the charged-current (CC) events from ν_μ interactions and of the background from ν_e CC interactions are shown in Fig. 5. The full curves were obtained assuming a realistic focusing system (single horn). The extreme cases of perfect focusing and unfocused beam are also reported.

The radial distribution of the beam at the detector site as expected with a horn/reflector system is relatively flat with nominal radius of the order of 2 km [5], see Fig. 6. Therefore the beam alignment to point the far detector at Gran Sasso should be maintained within 2 mrad. This precision is considered well within the capabilities of present technology.

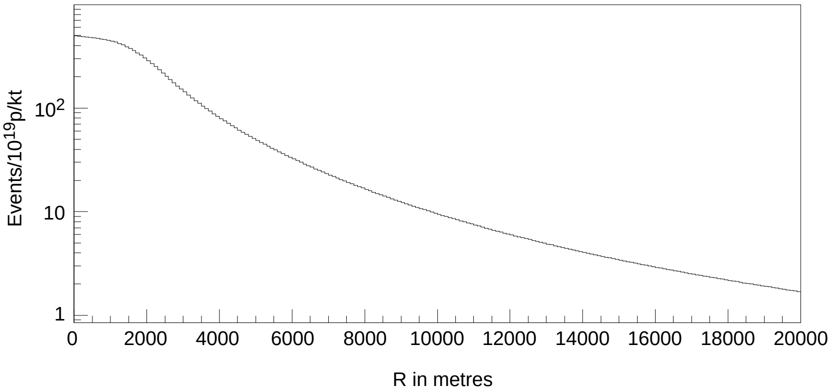

Figure 6: Neutrino flux radial distribution at Gran Sasso [5]. The vertical axis corresponds to the total number of ν_μ CC events per kton, with the CERN SPS delivering 1×10^{19} protons on target at an energy of 450 GeV. See Table 1, first row, for the focusing optics specifications.

The $\nu_{\rm e}$ contamination is at the $\leq 1\%$ level and is a limiting factor for the mixing angle sensitivity in the $\nu_\mu \rightarrow \nu_{\rm e}$ oscillation sector. Electron neutrinos are produced by kaon and muon decays. Those from muons are concentrated at low energies and are typically produced towards the end of the decay pipe since they originate from secondary decays. Only a minor limitation of the $\nu_{\rm e}$ background can be obtained by shortening the decay tunnel length but at the expense of a strong reduction in the ν_μ flux.

Neither study has so far considered a possible near detector. In principle a beam monitor should provide accurate measurements of the neutrino beam characteristics, which serve as input for the calculation of beam properties at the far detector. However, in the case of a long-baseline neutrino beam, this function is made difficult by the fact that the beam is quite different at the near and far detector locations. The transverse dimensions of the beam are smaller or larger compared, respectively, with the near or far detector dimensions. Furthermore, the far detector observes only a small fraction (those emitted at very small angles) of the neutrinos generated at the source and observed by the near detector. This requires delicate Monte Carlo corrections on the beam monitor measurements, affecting the systematic error on the beam calculations at far distance. On the other hand, the large statistics of events collected in the near detector could be very helpful for neutrino cross-section measurements and for tuning the event reconstruction procedure, necessary for a precise evaluation of the detector's systematic uncertainties. This is particularly important in the neutrino oscillation search with disappearance methods.

In conclusion, the two independent studies for a possible CERN–Gran Sasso long-baseline neutrino beam provided consistent information, indispensable for the development of ideas and proposals for future experiments at Gran Sasso: such a neutrino beam can produce of the order of one thousand detected events per year per kiloton in a detector placed at Gran Sasso, assuming the running of the SPS at 450 GeV/c and keeping conservatively the beam intensity on target at the current level of 1×10^{19}pot/year. The given number of events and the neutrino energy depend on the choice of the realistic focusing optics; eventually the energy spectrum could be tuned in order to enhance the sensitivity to the desired oscillation parameter region. The ν_{e} contamination is a limiting factor for the mixing angle sensitivity, but at far distance from the source its level is limited to $\leq 1\%$ of the ν_μ rate. The presence of a possible near detector has not been considered, so far, in the CERN–Gran Sasso beam calculations.

2.2 Experiments at Gran Sasso

Some experiments for long-baseline neutrino detection have been proposed recently by submission to the Gran Sasso Scientific Committee of a Technical Proposal 'ICARUS' or of an Expression of Interest 'NOE' and 'RICH'3). We present here a brief review of the technical solutions and of the physical capabilities of the proposed experiments.

ICARUS

ICARUS [12] is a multikiloton liquid argon time projection chamber. A precise proposal was originally made by C. Rubbia in 1977 [13]. The detector is homogeneous, continuously sensitive, self-triggering and able to provide 3-D images of any ionizing event like an electronic bubble chamber. Particle identification is available by measuring the ionization charge per unit length (proportional to $\mathrm{d}E/\mathrm{d}x$) and the range of the stopping particles. The detector is also an excellent electromagnetic calorimeter of very fine granularity and high accuracy.

The ultrahigh purity of the liquid argon is assured by a fast and effectual purification system developed in a R&D phase [14]. The purity level achieved with this system is such that free electrons, produced by ionization along the tracks, can drift over distances of several metres in a uniform electric field. The 3-D readout is performed with a chamber, consisting of a number of parallel wire planes and strip planes on printed boards, located at one end of the sensitive volume. The coordinate along the electric field is given by a measurement of the drift time, provided that the drift speed is known. The other two coordinates are measured without ambiguity by the induction and collection signals, from the drifting electrons, on the wire and strip planes. The wire pitch has to be chosen to have the best possible space resolution ($2 \div 5$ mm). It defines the 3-D pixel (or 'bubble').

During an intensive R&D programme on a reduced-scale prototype (3 ton of liquid argon) [15] all the main technological problems of this innovative technique were solved and measurements of the relevant physical parameters were performed. In Fig. 7 we report a cosmic ray event recorded in the ICARUS 3-ton prototype.

The ICARUS technique opens a potentially new and broad physics programme. A proposal for a 5 kton multipurpose detector, Fig. 8, was submitted to the Gran Sasso Laboratory in 1993 and approved by the Gran Sasso Scientific Committee in 1994. The approval for funding is expected from INFN in summer 1995. The physics programme focuses on two main fundamental issues [12]: nucleon decay and neutrino physics. The neutrino sector is being investigated both through the study of long-baseline neutrinos from a CERN beam and through the study of atmospheric neutrinos. Even though ICARUS is not optimized to study solar neutrinos, this issue is an important part of the programme.

---

3) Another expression of interest for a magnetized iron calorimeter for long-baseline neutrino detection (GeNIUS) has been submitted to the Gran Sasso Laboratory by some US Groups [11]. At present, the interest in this experiment seems not to be supported anymore.

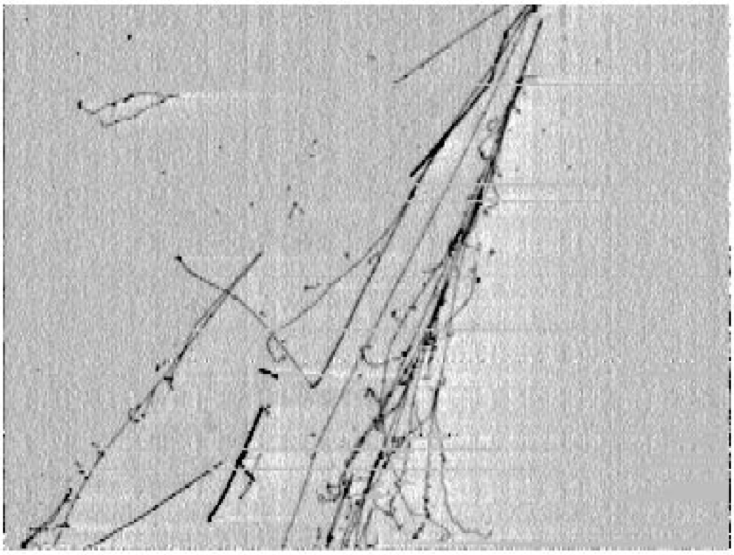

Figure 7: Cosmic ray shower observed in the ICARUS 3-ton prototype at CERN. The drift direction is along the horizontal axis spanning a distance of about 40 cm. The vertical axis corresponds to 192 sense wires with a 2 mm pitch. Each electron in the conversion pair visible at the upper left corner of the picture has about 5 MeV of energy and corresponds to the energy range of ^8B solar neutrinos in ICARUS. Also clearly visible near the centre of the figure is a $\pi^+ \rightarrow \mu^+(\nu_\mu) \rightarrow \mathrm{e}^+(\nu_\mathrm{e}\bar{\nu}_\mu)$ candidate as well as a clear electromagnetic shower.

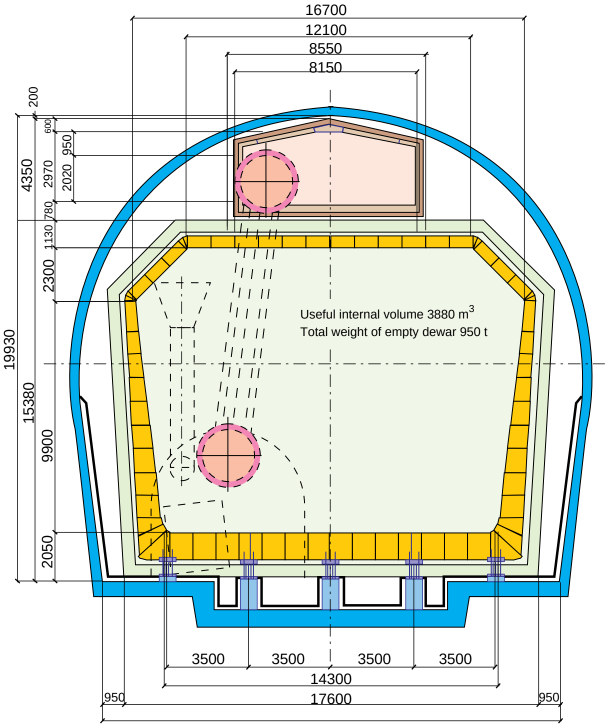

Figure 8: Schematic view of the 5 kton ICARUS detector to be built in the Gran Sasso Laboratory

The long-baseline neutrino issue is particularly important[4]. If oscillations are confirmed in the study of atmospheric neutrinos, it would be of great interest to use the CERN long-baseline neutrino beam, which gives sensitivity to the same region of the oscillation parameter plane, but with a much smaller systematic error. In particular, it will be possible to establish whether the oscillations observed with atmospheric neutrinos are $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_{\rm e}$.

In the $\nu_\mu \rightarrow \nu_{\rm e}$ channel, the neutrino oscillation study consists of searching for charged-current reactions of $\nu_{\rm e}$, with an electron producing an electromagnetic shower. The background consists of genuine electrons from $\nu_{\rm e}$'s present in the initial beam and of π^0's, faking electrons, from ν_μ neutral-current interactions. In ICARUS, π^0's can be identified from their decay properties (separation in the photon showers), from the shape of the shower, and from ionization information.

In the $\nu_\mu \rightarrow \nu_\tau$ channel, different methods can be used to study neutrino oscillations. Among these, the direct ν_τ search is particularly interesting because it relies on the unique features of the ICARUS detector: one can select the lower multiplicity event sample from $\nu_\tau + {\rm Ar} \rightarrow \tau + {\rm p}; \rightarrow \tau + {\rm p} + \pi^0; \rightarrow \tau + {\rm p} + \pi^+$ reactions and with semileptonic τ decay ($\tau \rightarrow {\rm e} + \nu_\tau + \bar{\nu}_{\rm e}$) [$BR = 17.8\%$]. The ability to reconstruct the outcoming proton in quasi-elastic reactions ($\langle E_{\rm p} \rangle = 200$ MeV) is unique to ICARUS. Applying additional kinematical cuts (aplanarity in the transverse-momentum plane and inelasticity condition) no background is left. The statistics are limited in this case (about 50 events per year from Ref. [6]) but the resulting sensitivity is large enough to cover the Kamiokande allowed oscillation region. The sensitivity in both channels has been studied using the beam simulation [6] and results are reported in Fig. 9.

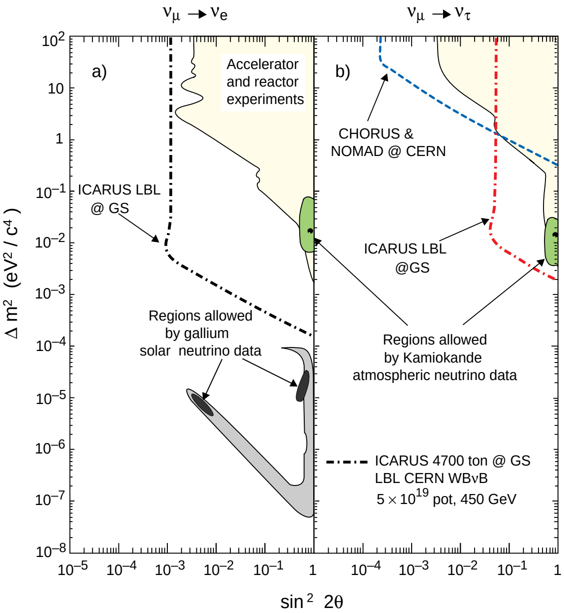

Figure 9: ICARUS sensitivity to (a) $\nu_\mu \rightarrow \nu_{\rm e}$ oscillations and (b) $\nu_\mu \rightarrow \nu_\tau$ oscillations. The ICARUS contour lines define regions excluded at 90% C.L. after three years of exposure. The regions excluded by previous accelerator and reactor experiments are reported as well as the allowed regions from the recent atmospheric neutrino study [16] of Kamiokande.

---

[4] The renewed interest of the CERN Laboratory in realizing such a facility [2] was initially triggered by the ICARUS request.

NOE

NOE [17] is a fast, massive, fine-grained calorimeter based on scintillating-fibre technology with high detection efficiency for both long-baseline neutrino beams and atmospheric neutrinos. This type of technology, in contrast with multilayer calorimeters, if suitably designed, provides more than 2-D symmetry, placing this solution close to detectors based on liquid media, like ICARUS and Kamiokande, where the 3-D symmetry allows full solid-angle coverage. The advantage, in comparison with liquid detectors, is that its solid structure is more stable and easy to handle. Moreover, the high time resolution allows one to identify the direction of the interaction and the distinct signature of hadronic showers provides a good selection of neutral-current events, particularly important in long-baseline neutrino investigations.

NOE is a full active modular structure easily extendible. It consists of a 4 kton calorimeter, divided into four identical blocks. A 2 kton muon detector completes the experimental apparatus. Each calorimeter block ($8 \times 6.4 \times 8\ \mathrm{m}^3$) is composed of a large number of submodules, the so-called ‘Basic Modules’ (BM), 2 ton each, logically segmented in four so-called ‘Basic Calorimeter Elements’ (BCE), see Fig. 10.

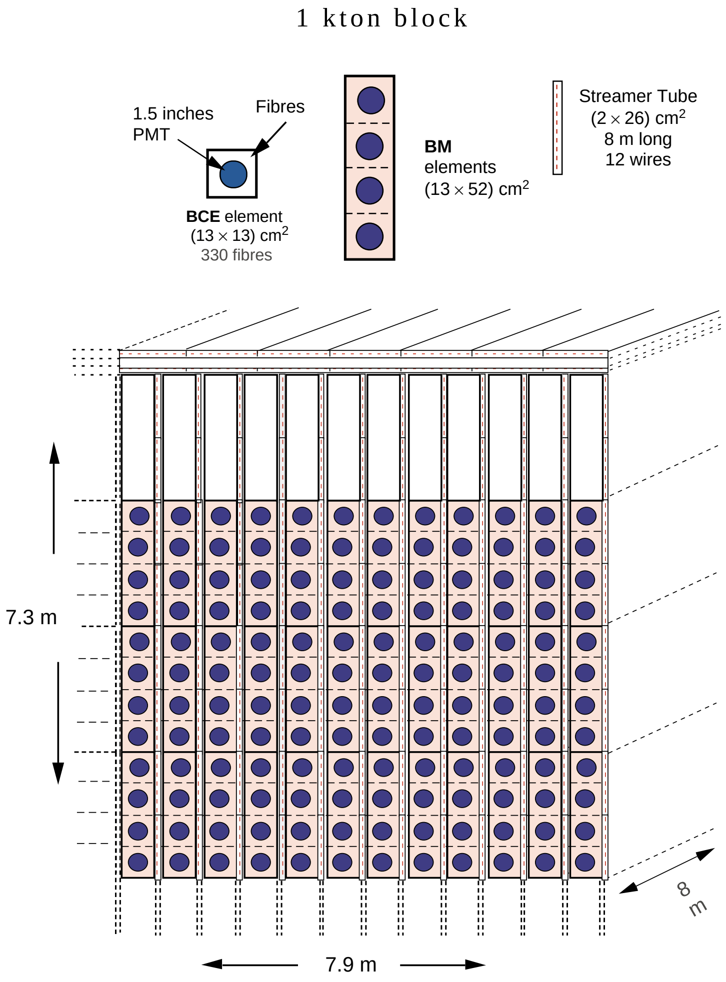

Figure 10: Schematic view of the NOE experiment with details of the detector structure

Vertical streamer tube planes are positioned interleaved between the BCE layers. Fibres are OR-ed together at one side of the BCE and collected in a 3×3 or 4×4 matrix to be read by a multianode PMT or HPD device. Such a readout allows energy and crossing-time measurement and the recording of the event topology. The BCEs in the basic module are 8 m long

13×13 cm square bars of magnetite, an inexpensive iron ore, as radiator, with 330 scintillating fibres as active component. The fibres (5 m attenuation length) are randomly located inside the bar, in order to guarantee the detector isotropy, and parallel to the bar axis. This makes the 2.5 radiation lengths of a BCE completely active. A BCE prototype has already been constructed and successfully tested with cosmic rays. The energy resolutions have been evaluated by means of a GEANT Monte Carlo simulation. They are, respectively, $\sigma_{\rm elm}(E)/E = 16\%/\sqrt{E}$ and $\sigma_{\rm had}(E)/E = 30\%/\sqrt{E}+7\%$. Particle identification is probably one of the main problems in neutrino oscillation studies. The capability of this detector to measure ionization losses (ΔE), in several path intervals (Δl) along the particle track, from the BCEs, allows particle identification using the $\Delta E/\Delta l$ versus range method. The streamer-tube tracking system surrounding the calorimetric elements improves particle identification. A complete study of this fundamental issue is under way and a detector design optimization will follow.

The expected rates of long-baseline neutrino interactions, based on the beam simulation [5], is of about 4700 CC events per year. Sensitivity to neutrino oscillation can be evaluated by using the NC/CC ratio, i.e. separating events with muon and without muon. Preliminary simulations indicate that the high granularity of the NOE detector might allow one to identify τ's in a ν_τ appearance search through kinematical cuts and energy distributions as proposed by the NOMAD experiment at CERN.

RICH

RICH [18] is a large Cherenkov Ring Imaging counter that can serve as both target and detector for long-baseline neutrinos. It consists of a cylindrical radiator, 20 m in diameter and 50 m long filled with argon gas (15 bar) at room temperature. The sensitive mass is of 400 tons and the Cherenkov threshold is $\gamma_{\rm thr} = 10$. The mirror for reflecting the photons is spherical with a radius of $R_{\rm M} = 100$ m. The photon detector is on the focal surface of the mirror, namely on an upstream spherical surface, $R_{\rm D} = 50.13$ m in radius [19]. The pixel size considered for the photon detector is $30 \times 30\ {\rm mm}^2$, this corresponds to 3×10^5 channels. A 3 kton water target is located in front of the RICH radiator tank. Downstream from the radiator and mirror there may be a large surface tracking device equipped with an iron absorber to identify muons and measure the direction of secondary charged particles, and so determine the interaction vertex. A schematic view of the RICH detector with the external water target and tracker is shown in Fig. 11.

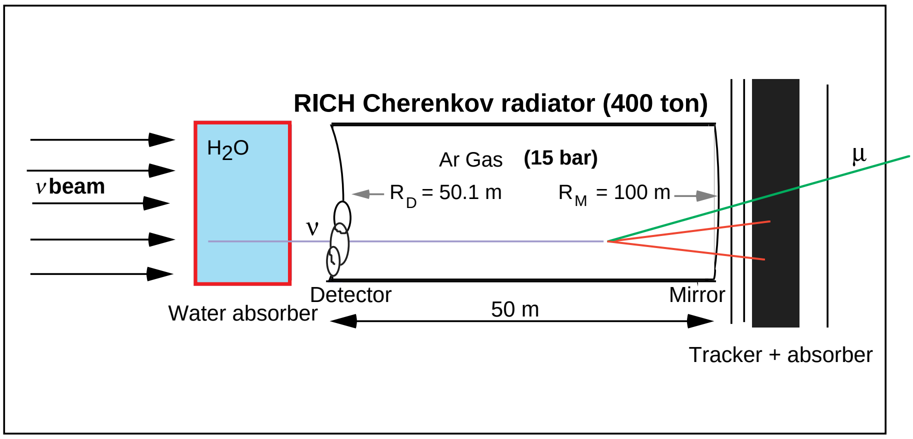

Figure 11: Schematic view of the RICH experiment with details of the detector layout

An important and unique feature of the long-baseline RICH detector is that it can be placed above ground at the external Gran Sasso Laboratory (a suitable area has to be found) in a tank (or concrete bunker) capable of being pressurized to 15 bar with argon gas. If $\mathrm{C_5F_{12}}$ gas is used at atmospheric pressure (to avoid a high-pressure tank or bunker) the threshold would rise to $\gamma_{\mathrm{thr}} = 17$.

Throughgoing charged particles will produce photoelectrons on the ring images. With a relatively easy pattern recognition, based on stereographic projection of the Cherenkov rings, even complicated events can be completely reconstructed. The reconstructed Cherenkov angle would determine particle momentum measurement ($0.3 \leq \sigma_p/p \leq 7$ %). Particle velocity is obtained from the Cherenkov angle, hence the mass is determined ($1 \leq \sigma_m/m \leq 2\%$). The RICH image also determines particle direction measurement ($\sigma_\theta = 1$ mrad), hence transverse momentum as well as momentum, thus direct (from ν_μ) and indirect muons (from ν_τ) can be separated by cuts in the (p_{T}, p) plane. This feature can provide the signature for neutrino oscillations. A ν_τ appearance experiment can be performed identifying the signal of indirect muons (ν_τ X $\rightarrow \tau$ X$'$; $\tau \rightarrow \mu\nu_\tau$) from the background of direct muons (ν_μ X $\rightarrow \mu$ X$'$). For any initial neutrino energy, background muons tend to have higher momentum, for a given transverse momentum, than do the signal muons. Thus, cuts in the (p_{T}, p) plane can discriminate the two processes with rejection power $> 10^3$.

The expected rate of events, based on the beam simulation [5], is of about 200 ν_μ interactions per year where all secondary particles ($\gamma > 10$) have their momentum, direction, and mass determined by RICH. In addition, about 1500 events per year would be recorded from the water target. Here, only muons emerge from the interaction but their momentum, direction, and mass are well measured by RICH. The study of the RICH sensitivity to oscillation in the $\nu_\mu \rightarrow \nu_\tau$ channel is under way.

The possibility of making a spot-focusing Cherenkov calorimeter out of the water target is now being considered. This would allow (p, p_{T}) measurements also for ν_{e} interactions.

3 CONCLUSIONS

A feasibility study has shown that it is technically possible to send a CERN neutrino beam to Gran Sasso in Italy, which happens to be in a favourable azimuthal direction with respect to one of the planned SPS–LHC proton transfer lines. The beam could be available five years after approval, i.e. at the earliest during the year 2000.

Two independent studies for a possible CERN–Gran Sasso long-baseline neutrino beam provided reliable indications on the beam properties, indispensable for the development of ideas and proposals for future experiments at Gran Sasso. A CERN neutrino beam, with standard target and optics solutions, can produce of the order of one thousand detected events per year per kiloton in a detector placed at Gran Sasso, assuming the running of the SPS at 450 GeV/c and keeping conservatively the beam intensity on target at the current level of 1×10^{19} pot/year. In dedicated mode the reachable intensity could be at least a factor three larger. The ν_{e} contamination is a limiting factor for the mixing angle sensitivity but at far distance from the source its level is limited to $\leq 1\%$ of the ν_μ rate.

Three experiments with totally different detection techniques have been proposed at Gran Sasso.

The 5 kton liquid argon TPC of the ICARUS detector is based on an innovative technology, firmly established by an intense R&D phase. It works as an electronic bubble chamber with the ability to provide 3-D imaging with an excellent calorimetric response. Long-baseline neutrino oscillations in both the ν_{e} and ν_τ channels can be studied with high sensitivity. The 4 kton NOE detector is a fast, granular, and quasi-isotropic device using scintillating-fibre technology. Preliminary studies on the achievable sensitivity to neutrino oscillations have shown encouraging results. Finally, the RICH detector is a Cherenkov Ring Imaging counter. It consists of a pressurized radiator with 400 ton of argon gas, with a 3 kton water target in front and a tracking system placed downstream, on the neutrino beamline. An important and unique feature of the long-baseline RICH detector is that it can be placed above ground at the external Gran Sasso Laboratory.

We conclude by underlining that from both the CERN and the INFN Gran Sasso Laboratories a strong interest has been shown in this common project of a long-baseline neutrino beam: together with the LHC, the construction of a long-baseline neutrino beam facility is considered at CERN as an interesting, possible issue for the coming years (as recently stated at the last SPSLC Meeting in Cogne, May 1995), and at Gran Sasso the construction, recently approved, of new experimental halls in the underground laboratory will allow the hosting of at least two experiments for long-baseline neutrino detection.

Acknowledgements

All the material reported in this review is the result of the valuable work of a number of colleagues and friends. I would like to express my thanks to them. First of all to F. Pietropaolo for the information on his beam simulations and for the enlightening discussions on many aspects of long-baseline neutrino physics; to A. Ball and S. Katsanevas for the information on their calculations of the CERN long-baseline neutrino beam; to T. Ypsilantis for the advice on the RICH detector; and to F. Guarino and G.C. Barbarino for the advice on the NOE detector. I am also grateful to C. Rubbia for triggering my interest on the long-baseline neutrino issue and to all my friends in the ICARUS Collaboration, in particular to G. Piano Mortari, P. Picchi, C. Montanari, and J.-P. Revol for their help in preparing this document. I would also like to thank D. Michael for cooperation in the organization of the ‘Gran Sasso Meetings on Long Baseline Neutrino Experiments’. Finally I would like to thank the Director of the Gran Sasso Laboratory, P. Monacelli, for giving me the opportunity to prepare this review, and M. Greco for inviting me to this most interesting Conference at La Thuile.

References

[1] LNSD Collaboration, Neutrino oscillation studies at LAMPF, Nucl. Phys. B (Proc. Suppl.) **38** (1995) 229.

[2] A.E. Ball, B. Bianchi, J.-P. Revol, G.R. Stevenson and E. Weisse, CERN beams for long baseline neutrino oscillation experiments, CERN–SL Note 92–75 (BT) (1992).

[3] E. Weisse, presented at the Gran Sasso Meeting on Long Baseline Neutrino Experiments, CERN, March 1995.

[4] H. Wenninger et al., Present and Future Neutrino Beams at CERN, Nucl. Phys. B (Proc. Suppl.) **38** (1995) 241.

[5] A.E. Ball, S. Katsanevas and N. Vassilopoulos, Design study for a long baseline neutrino beam, CERN/ECP 95–13.

[6] F. Pietropaolo, presented at the Gran Sasso Meeting on Long Baseline Neutrino Experiments, Gran Sasso, Dec. 1994.

[7] E. Weisse, A. Ball and G. Stevenson, presented at SPSLC Meeting, Cogne, May 1995.

[8] GEANT – detector description and simulation tool, CERN Program Library Long Writeup, Vers. 3.21, W5013 (1993).

[9] FLUKA92, Proc. of the Workshop on Simulating Accelerator Radiation Environments, Santa Fe, USA, Jan. 1993;
A. Fasso et al., Nucl. Instrum. Methods Phys. Res. **A 332** (1993) 459.

[10] NESTOR: a neutrino particle astrophysics underwater laboratory for the Mediterranean, Proposal by the NESTOR Collaboration, 2 vols., (May 1995).

[11] G.J. Alner et al., Expression of interest for a long baseline neutrino oscillation experiment using a CERN beam and a large magnetic sampling calorimeter at Gran Sasso, Expression of Interest submitted to the Gran Sasso Scientific Committee (1994).

[12] ICARUS: a second-generation proton decay experiment and neutrino observatory at the Gran Sasso Laboratory, Proposal by the ICARUS Collaboration, LNGS Note 94/99-I & II (1994).

[13] C. Rubbia, CERN-EP/Internal Report 77–8 (1977).

[14] P. Cennini et al., ICARUS Collaboration, Nucl. Instrum. Methods Phys. Res. **A 333** (1993) 567.

[15] P. Benetti et al., ICARUS Collaboration, Nucl. Instrum. Methods Phys. Res. **A 332** (1993) 395;
P. Cennini et al., ICARUS Collaboration, Nucl. Instrum. Methods Phys. Res. **A 345** (1994) 230.

[16] Y. Fukuda et al., Kamiokande Collaboration, Phys. Lett. **B 335** (1994) 237.

[17] G.C. Barbarino, A possible experiment to search for atmospheric neutrino and long baseline neutrino oscillations, presented at the Gran Sasso Meeting on Long Baseline Neutrino Experiments, Gran Sasso, Dec. 1994;
M. Ambrosio et al., LNGS/Note 94–112 (1994);
M. Ambrosio et al., A new design scintillating fiber calorimeter to search for neutrino oscillations in massive underground detectors, to be published in Nucl. Instrum. Methods Phys. Res. (1995).

[18] D. Hatzifotiadou et al., A large area RICH for long baseline neutrinos, CERN-LAA/Note PI-94–17 and Collège de France LPC/Note 94–29 (1994);
T. Ypsilantis, A large area RICH for long baseline neutrino experiment, presented at the Gran Sasso Meeting on Long Baseline Neutrino Experiments, Gran Sasso, Dec. 1994 and CERN, March 1995;
T. Ypsilantis, private communication (1995).

[19] T. Ypsilantis and J. Séguinot, Nucl. Instrum. Methods Phys. Res. **A 343** (1994) 30.