CERN/SPSC 98-25
SPSC/M612
LNGS-LOI 8/97, Add.1
October 9, 1998

The OPERA ν_τ appearance experiment in the CERN-Gran Sasso neutrino beam

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ABSTRACT

This document outlines the progress in the design and the expected performance of the OPERA experiment. It is designed for the appearance search of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation in the parameter region indicated by Super Kamiokande, as the explanation of the atmospheric neutrino deficit. OPERA is a long baseline experiment, to be located in the Gran Sasso Laboratory in the NGS neutrino beam from the CERN SPS. The detector is based on a massive lead/emulsion target. Nuclear emulsions are exploited for the direct observation of the decay of the τ lepton, produced in ν_τ charged current interactions. OPERA has a high discovery potential which is ultimately due to a very low background level and could therefore play a decisive role in the clarification of the experimental scenario.

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Introduction

The Super Kamiokande Collaboration [1] has claimed the observation of neutrino oscillation as an explanation of the apparent deficit of atmospheric muon neutrinos, following earlier indications from the Kamiokande experiment [2]. A small Δm^2 ($\sim 10^{-2} - 10^{-3}$ eV^2) and a large mixing angle ($sin^2 2\theta > 0.8$) are favoured [3]. The CHOOZ experiment excludes to a large extent the possibility of $\nu_\mu \leftrightarrow \nu_e$ oscillation [4], which is also disfavoured by the Super Kamiokande data. This leaves both $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{sterile}$ oscillation as possible explanations with a slight preference for the first hypothesis [3]. The above parameter region is accessible by long-baseline accelerator experiments.

From 1999 onwards, the K2K experiment [5] will be searching for ν_μ disappearance by using the neutrino beam from KEK to Super Kamiokande. Given the low neutrino beam energy, which is below the kinematical threshold for τ production, K2K will not perform a $\nu_\mu \leftrightarrow \nu_\tau$ appearance search needed to reveal the source of the Super Kamiokande signal. This is the objective of the OPERA[3] experiment. It aims at a high sensitivity search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation by exploiting nuclear emulsion for the direct detection of the τ lepton, produced in the interaction of the ν_τ with the target. OPERA is designed for a long baseline search in the proposed NGS beam [6] from the CERN SPS to the Gran Sasso Laboratory. Thanks to the capability in identifying electrons and to the small contamination of ν_e in the beam, OPERA could also accomplish a $\nu_\mu \leftrightarrow \nu_e$ oscillation search. The design principles of the experiment may be found in the Letter of Intent [7].

The technique of nuclear emulsion has found a large scale application in the target of the CHORUS experiment [8] and can be further improved for future $\nu_\mu \leftrightarrow \nu_\tau$ oscillation searches (see references quoted in [7]). In [9] and [7] the conceptual design of OPERA, a massive detector capable of exploring the low Δm^2 region ($\sim 10^{-3}$ eV^2) with high sensitivity was outlined. In OPERA, emulsions are used exclusively as high precision trackers, unlike CHORUS where they constitute the active target itself. The extremely high space resolution of the emulsion is well suited for the detection of the short-lived τ lepton produced in ν_τ interactions, as the direct observation of the decay topology allows background reduction to a very low level. Emulsion experiments nowadays benefit from the impressive progress in the field of computer controlled microscopes read-out by CCD cameras, with automatic pattern recognition and track reconstruction. After its pioneering work, the Nagoya group of the CHORUS and OPERA Collaborations is close to deliver a third generation automatic system about 1000 times faster than semi-automatic systems [10]. Improvements are expected from the intense R&D programmes underway at CERN, in Germany, Italy and Japan.

The OPERA design

The starting point in the design of OPERA is the Emulsion Cloud Chamber (ECC) (see references quoted in [7]). The ECC provides a massive target made up of a sandwich of dense passive material plates and thin emulsion sheets (ES). The ECC has been used for several applications and was recently proposed for long-baseline experiments searching for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation (see references quoted in [7]). Employing metal plates as a target with the emulsion used only for tracking, the target mass can be increased by orders of magnitude as compared to conventional emulsion experiments. However, in the ECC, direct observation of the τ decay "kink" performed by CHORUS is replaced by an impact parameter

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[3] Oscillation Project with Emulsion-tRacking Apparatus.

measurement. The OPERA concept is an evolution of the ECC. The idea is to insert a “gap” between consecutive emulsion sheets. This “empty” space between the ES allows direct detection of the τ decay kink, which makes this approach far superior to the impact parameter measurement done with the standard ECC (Fig. 1). This results in a substantial background reduction.

The present design of the OPERA detector, whose optimization is underway, is a lead/emulsion target subdivided into “bricks”. Each brick, weighing about 8 kg, has dimensions orthogonal to the beam direction of 15×15 cm^2. It consists of a sequence of 30 sandwiches, each composed of a 1 mm thick lead plate followed by an emulsion sheet (ES1), a spacer of 3 mm, and another emulsion sheet (ES2) as shown in Fig. 1. ES1 is made up of a pair of emulsion layers 50 μm thick[4], on either side of a 100 μm plastic base. The plastic base is 200 μm thick in ES2, in order to improve the angular resolution. The spacer consists of very low density material. Charged particles give two track segments in each ES. The ~ 1 μm granularity of the emulsion layers ensures redundancy in the measurement of particle trajectories. Along the beam axis, the total thickness of one brick is about 13 cm. A matrix of adjacent bricks, arranged in a plane structure, forms a target module. The modularity of the target allows to conceive a total target mass (lead) of $\sim$ 800 ton, suited to meet the physics goal of the experiment. The target structure also permits the removal of those bricks where an interaction took place and to analyse their emulsion sheets soon after.

If a τ is produced, it will decay within a few millimeters, either in the lead plate or, *e.g.* in the low density spacer between ES. A source of background to the τ decays in the lead (“lead” events), detected through an impact parameter measurement, is potentially given by hadron re-interactions. One of the primary hadrons may re-interact in the vertex lead plate giving products not seen by the emulsion, hence simulating the charged 1-prong decay of the τ. For decays in the spacer (“gap” events), the τ is detected by measuring the angle between the charged decay daughter and the τ directions. This kink angle is due to the invisible neutrino(s) produced in the decay. For its measurement, the directions of the tracks before and after the kink are reconstructed (in space) by means of the first pair of ES downstream of the lead plate where the primary vertex occurred (Fig. 1).

By requiring that the decay occurs in the gap one rejects the re-interaction background. The τ decays in the gap are classified as “gold plated” events with virtually no background. The “lead” events, however, are not lost. They can contribute to the signal by the application of hard cuts for background rejection.

Electronic detectors, placed behind each 13 cm target module, are needed to identify the actual brick where the neutrino interaction took place and to guide the scanning. OPERA at the Gran Sasso is naturally shielded against non-penetrating particles and it is exposed to a neutrino beam without halo muons. This leads to a low density of background tracks “stored” in the emulsion and removes the need for a precise location of individual tracks in the ES by electronic trackers. Therefore, a moderate space resolution can be tolerated ($\sim$ 1 cm). The main purpose is to determine the event shower-axis, hence locating the brick whose emulsion must be scanned. Magnetized iron toroids placed downstream of the target, have the task of identifying muons with high efficiency and measuring their charge for background reduction.

The detector structure

Most of the features of OPERA discussed in the following (detection efficiency, background and sensitivity) are determined at the brick level, being rather independent of the way the target is actually

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[4] The number of grain hits in 50 μm is adequate for track reconstruction by means of automatic scanning devices.

assembled. The detector design is based on a modular structure. Each module consists of a target section of ~ 5 m of transverse dimension followed by a muon detection system. Longitudinally, the entire detector is at most 35 m long in the underground gallery. We are presently working on the design to optimize: 1) muon ID efficiency; 2) brick handling (insertion and removal); 3) detector installation in the gallery.

The performance requirements for the electronic detectors are: ~ 1 cm space accuracy, high efficiency and long-term reliability. The large total area (about 2500 m^2) restricts the choice to mature technologies previously used in applications of a similar scale and suitable for industrial production. The preferred option for the OPERA target section is based on narrow scintillator strips read-out by WLS fibers coupled to photodetectors. An alternative solution is resistive plate chambers (RPC) operating in the streamer mode, with two sensitive layers equipped with two-dimensional digital strip read-out. Both options feature a few ns time resolution sufficient for the local trigger.

The trackers for the muon system must have the space resolution of ~ 1 mm. This requirement can comfortably be met by the use of mini-drift tubes (MDT) made of extruded comb-like aluminium profiles and equipped with digital and drift-time wire read-out. The sensitive cell size is 9×9 mm^2. Both streamer and proportional operating modes are possible. A muon station consists of several MDT planes rotated with respect to each other.

The main option for the muon system consists of 5 cm thick toroidally-magnetized octagonal steel plates arranged in ~ 75 cm long magnet modules. The magnetization coils run through a 10 cm hole at the center of each plate in a module. The average B-field in iron is about 1.5 T. Each plate is followed by a 1 cm thick plane of plastic scintillator strips with WLS fiber read-out. The calorimetrized magnets act as a hadronic tail catcher and, in addition, have muon tracking and ranging capabilities. The arrangement of the muon stations will allow for muon momentum determination with no worse than 30% resolution. The energy of neutrino-induced electromagnetic and hadronic showers is determined by measuring pulse-heights in the scintillators. The expected energy resolution is about $80\%/\sqrt{E}$.

Neutrino beam and events

The original NGS "reference" neutrino beam from the CERN SPS to the Gran Sasso is described in [6]. A further optimization of the ν_τ interaction yield was then carried out in [11], serving as a basis for the new NGS beam design developed by the CERN/INFN Technical Committee [12]. The expected neutrino flux at the Gran Sasso location, the mean neutrino energy and the number of interactions for the different neutrino species of the new beam are presented in Table 1. The rate of interactions is given separately for deep-inelastic and resonance plus quasi-elastic (QE) events. The expected yield of interacting ν_τ is $2.84/(10^{19}$ pot $\times$ kton), computed for $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 (at full mixing) and with standard sets of neutrino cross sections.

We consider two running schemes, as indicated by the CERN SPS and Gran Sasso Committees for the determination of the experiment performance. The first one, called the "baseline" scheme [12], foresees a three years' run with 3×10^{19} pot/year from the SPS. The second one ("realistic") assumes a four years' run with an average of 4×10^{19} pot/year. It presumes similar performance of the accelerator complex as over the past years of operation. The total number of expected ν_μ interactions in the OPERA target for the "baseline" ("realistic") running scheme is 4250 (7500) charged currents (CC) and 1400 (2500) neutral currents (NC). The number of interacting ν_τ is ~ 20 (35) assuming that oscillation occurs with

	ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$
flux ($\nu/(10^{19} pot \times m^2)$)	6.7×10^{10}	2.5×10^9	3.8×10^8	5.9×10^7
relative interaction rate	1	0.02	0.008	6×10^{-4}
mean neutrino energy (GeV)	20.4	21.0	31.5	26.3
deep inelastic CC ($evts/(10^{19} pot \times kton)$)	540	10.4	4.7	0.3
resonances+QE ($evts/(10^{19} pot \times kton)$)	50	1.3	0.3	–

Table 1: Features of the NGS beam at the Gran Sasso location [12].

Δm^2=2.5×10^{-3} eV^2 and full mixing.

Detection efficiency for the τ decay

The signal of the occurrence of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation is the CC interactions of τ neutrinos in the detector target: $\nu_\tau N \to \tau^- X$. The detection of the τ lepton decay in the final state identifies this reaction through the decay modes into single hadron, muon and electron: $\tau^- \to h^- \nu_\tau (n\pi^0)$, $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$, $\tau^- \to e^- \nu_\tau \overline{\nu}_e$. Despite its distinctive experimental signature, the three-pion decay mode has an expected background which is not negligible and, therefore, it is not considered for the present sensitivity estimate. The τ detection efficiency of OPERA has been evaluated by simulations which take into account the experience gathered with the CHORUS experiment. The efficiency depends on the kinematical features of the events, and is therefore a function of the oscillation parameters. In the following, the estimates are given for a "low" (2.5×10^{-3} eV^2) Δm^2 and full mixing.

The event finding efficiency in OPERA is essentially 100%, being determined by the electronic detectors. For events with a τ decaying in the spacer ("gap" events) one performs a direct kink detection. Given the NGS beam features and the τ decay kinematics, ϵ_{gap}= 42% is the probability of the τ decaying in the gap. An additional factor determining the detection efficiency (ϵ_{kink}) is given by the rejection of small-angle ($<$ 20 mrad) and very large-angle kinks ($>$ 500 mrad). The lower cut is due to the angular resolution (5 mrad) in the measurement of the kink angle in space by means of the four track segments in ES1 and ES2. The upper cut is motivated by considerations related to the scanning efficiency. The fraction ϵ_{kink} of τ decays with a kink angle in the useful range depends on the actual decay mode. It amounts to 91%, 88% and 83%, respectively for the hadron, muon and electron decay modes. Another factor is the geometrical detection efficiency ϵ_{geom} due to the fiducial volume cut of $\sim$ 90%, which has to be applied to take into account edge effects in the ES scanning.

The branching ratio (BR) for the τ decay into single charged hadron plus neutrals is about 50%. The total detection efficiency of this channel, $\epsilon_h = \epsilon_{gap} \times \epsilon_{kink} \times \epsilon_{geom} \times$ BR, amounts to 17%. Similar considerations apply to the muon and electron decay of the τ. The contributions of these two channels are nearly the same. The BR is 18% for both the decay modes, and an efficiency $\epsilon_\mu \sim \epsilon_e$ of 6% is obtained. The global detection efficiency for "gap" events, $\epsilon_G = \epsilon_h + \epsilon_e + \epsilon_\mu$, is high compared to other experiments and allows for a comparatively low target mass. It amounts to $\sim$ 29% for $\Delta m^2 \sim 2.5\times10^{-3}$ eV^2 and increases to 33% for larger Δm^2 values.

The “lead” events may also contribute to the oscillation signal. Only 1-prong electron and hadron decay modes are to be retained, due to the significant charm background to the muonic channel. The τ decay is identified by detecting a track with “large” impact parameter (IP) with respect to the others. The actual value of the cut on IP is determined by the effect of multiple scattering and angular resolution. This yields an efficiency $\epsilon_{IP} \sim 50\%$. An additional cut has to be applied, in order to reduce the background due to re-interactions. The cut rejects those events where the track with large IP has low momentum (*e.g.* < 2 GeV/c). It results in a detection efficiency reduced by a factor from 2.5 to 5, depending on the cut value. Folding in the efficiency for the τ to decay in the lead ($\epsilon_{lead} \sim 60\%$), the geometrical efficiency ($\epsilon_{geom} \sim 90\%$) and the BR for the electron and hadronic decay channels, a detection efficiency ϵ_L of the order of 5–10% is obtained for “lead” events in the low Δm^2 region. These events could well contribute to the OPERA sensitivity or be used for cross-checks and complementary analyses. However, we wish to stress that they are not included in the present sensitivity estimate, which only takes into account the “gold plated” “gap” events.

Background

The background evaluation has been performed by means of a full simulation including the beam features, the physics processes and the detector structure. The expected background sources for “gap” events are: 1) prompt ν_τ production in the primary proton target and in the beam dump; 2) re-interactions in the spacer; 3) decay of pions and kaons produced in CC and NC ν_μ interactions; 4) 1-prong decay of charmed particles.

The first two sources are negligible. For 10^{20} pot, the prompt ν_τ give 0.02 CC events over the detector fiducial volume. Due to the low density of the material which constitute the spacer (about 30 kg/m^3), the number of hadronic re-interactions which may simulate a “gap” decay is negligible. We estimate $< 1 \times 10^{-5} \times N_{CC}$ background events, where N_{CC} is the total number of CC events collected by OPERA.

The decay in the gap of pions and kaons produced in NC neutrino interactions can produce the topology of a candidate τ event. CC interactions are an additional source of this background if the prompt primary muon is undetected. The expected number of these background events is $3{\times}10^{-5} \times N_{CC}$.

Charmed particles are produced in CC and NC neutrino interactions through the reactions: a) $\nu_\mu N \to c\,\mu X$, b) $\nu_\mu N \to c\bar{c}\,\mu X$, c) $\nu_\mu N \to c\bar{c}\,\nu_\mu X$. These processes may constitute a background to the oscillation signal if one fails to detect the primary muon (a-b) or the charm partner (b-c). The most relevant source is given by single charm production (reaction (a)), since charmed mesons have mass and lifetime similar to those of the τ. If the primary muon is missed, a D^+ meson decaying in one charged particle (plus neutrals) can fake a genuine τ event, since the (positive) sign of the D^+ daughter is only measured for the muonic channel by the muon spectrometers. We obtain $8.1{\times}10^{-5} \times N_{CC}$ background events for the 1-prong hadronic D decay, $0.7{\times}10^{-5} \times N_{CC}$ events for the muonic channel and $2.2{\times}10^{-5} \times N_{CC}$ events for the electron channel. The background from associated charm production in CC and NC interactions has been estimated to $2.3{\times}10^{-5} \times N_{CC}$ events. In the case of the charm background QE and resonances are not relevant and only deep-inelastic CC events contribute. Similarly, the contribution from $\overline{\nu}_\mu$, ν_e and $\overline{\nu}_e$ to the charm background is negligible, as they constitute only a small contamination of the ν_μ beam.

For the three 1-prong τ decay modes together (“gap” events) OPERA will be left with $\sim 16{\times}10^{-5} \times N_{CC}$ background events with a decay topology (Table 2). Candidate events will undergo further kinematical analysis at the interaction and decay vertices [7]. The expected difference in the kinematics of

Background source	evts/10^3 CC	after kinematics
π and K decays	0.03	–
re-interactions	< 0.01	–
charm	0.13	0.06
TOTAL	0.16	0.06

Table 2: Number of background events (per 1000 CC events), for the different channels and for the "gap" sample.

τ decays with respect to background events is then exploited. An additional background rejection of a factor ~ 2 is estimated (Table 2), keeping high efficiency for the signal: 85% (95%) in the earlier defined low (high) Δm^2 region. Given the "baseline" ("realistic") running scheme, the total background for "gap" events amounts to 0.25 (0.45) events with an overall uncertainty of about 20%. Ongoing studies and future test measurements will determine which background rejection can finally be achieved by the kinematical analysis.

After the cuts described in the previous Section, for "lead" events a total of about $6\times10^{-5} \times N_{CC}$ background events survives, basically due to secondary interactions in the lead plate.

Sensitivity to $\nu_\mu \leftrightarrow \nu_\tau$ oscillation and discovery potential

The OPERA τ detection efficiency ϵ_G amounts to $\sim$ 33% for high Δm^2 and $\sim$ 29% for $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2. The ratio of cross sections $\sigma(\nu_\tau)/\sigma(\nu_\mu)$ is 0.43, considering deep-inelastic, resonances and quasi-elastic events. Given the fiducial volume cut, the number of detected CC neutrino interactions is 3820 and 6800, for the "baseline" and "realistic" running schemes, respectively. The sensitivity of the experiment has been evaluated with a method analogous to the one described in [13]. The energy dependence of the neutrino spectra and of the detection efficiencies have been taken into account and the conventional two-flavour mixing scenario has been assumed. For the "baseline" running scheme, the limit on the mixing angle (for large Δm^2) is $sin^2 2\theta_{\mu\tau} < 7.5\times10^{-3}$ (90% CL) under the hypothesis of no observed events and 0.25 estimated background events [14]. The corresponding minimum Δm^2 (for full mixing) is 1.6×10^{-3} eV^2. In the case of the "realistic" scheme, we obtain $sin^2 2\theta_{\mu\tau} < 3.8\times10^{-3}$ and a minimum Δm^2 of 1.1×10^{-3} eV^2. The corresponding exclusion plots are shown in Fig. 3 and Fig. 4.

The Super Kamiokande result from the measurement of the zenith angle dependence is consistent with large mixing angles and with a preferred Δm^2 range which extends, at the 90% CL, from about 5×10^{-4} to 6×10^{-3} eV^2. Fig. 3 and Fig. 4 also show the allowed parameter region (90% CL) as evaluated in [15] from a global fit of the different measurements by Super Kamiokande.

OPERA is an experiment designed for discovery. In Table 3 the number of detected τ events is listed as a function of Δm^2 (for full mixing), together with the expected numbers of background events for the "baseline" and the "realistic" running schemes. Since the unambiguous experimental signature leads to a very low background, these numbers quantify the discovery potential. In particular, assuming that $\nu_\mu \leftrightarrow \nu_\tau$ oscillation occurred with parameter values $\Delta m^2 = 2.5\times10^{-3}$ eV^2 and $sin^2 2\theta_{\mu\tau}$=1 (*i.e.* the Super

Δm^2 (eV^2)	SIGN.(realistic)	BG (realistic)	SIGN.(baseline)	BG (baseline)
1.8×10^{-3}	5	0.45	–	–
2.5×10^{-3}	9.4	“	5.2	0.25
5×10^{-3}	37	“	21	“
8×10^{-3}	90	“	51	“

Table 3: Detected τ events and background as a function of Δm^2 (for full mixing).

Kamiokande favoured values), a total of 5.2 (9.4) CC ν_τ interactions would be detected by OPERA, for the two running schemes. In Fig. 3 and Fig. 4 the 4 σ discovery contour is plotted in the $sin^2 2\theta$–Δm^2 parameter plane[5]. For full mixing this corresponds to $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2 ($\Delta m^2 = 1.8 \times 10^{-3}$ eV^2). In the case of a positive search, OPERA will be able to constrain the oscillation parameters by measuring the energy of the τ events. This can be achieved by means of the calorimetric measurement in the target and by the determination of the muon momentum by the spectrometers. Studies are underway to assess this issue quantitavely.

Search for $\nu_\mu \leftrightarrow \nu_e$ oscillation

The evaluation of the OPERA sensitivity to $\nu_\mu \leftrightarrow \nu_e$ oscillation is in progress. Together with the $\nu_\mu \leftrightarrow \nu_\tau$ appearance search this measurement will permit to perform a global three-flavour mixing analysis with a single experiment.

The primary vertex tracks in muonless events are measured to look for the occurrence of CC ν_e interactions. Electron identification is performed by following tracks into the ESs downstream of the vertex plate (see references quoted in [7]). We carried out simulations of the electron identification capability by means of multiple energy-loss measurements. The efficiency is a function of the material thickness traversed. A value ranging from 60 to 80% seems to be realistic.

In the experiment there are two main sources of background electrons. The first is given by the ν_e ($\bar{\nu}_e$) contamination of the ν_μ beam. The second is represented by the electrons from the Dalitz decay of neutral pions produced in NC ν_μ interactions ($\pi^0 \rightarrow e^+e^-\gamma$) and from photon to electron conversion in the lead plate ($\pi^0 \rightarrow 2\gamma$ followed by $\gamma N \rightarrow e^+e^-N$). The sensitivity of the measurement of the oscillation parameters is determined by two factors: the statistical error of the estimated number of background events and the systematic errors due to the uncertainty in the estimate of the ν_e content of the beam and to the uncertainty of the number of electrons produced by π^0.

The sensitivity of OPERA in searching for $\nu_\mu \leftrightarrow \nu_e$ oscillation is expected to be $\sim 10^{-2}$ in $sin^2 2\theta$ and $\sim 10^{-3}$ eV^2 in Δm^2. This region is interesting in relation to the the Kamiokande solution of the atmospheric anomaly [2], also explored by the CHOOZ reactor experiment [4]. It is worth noting that the present estimates of the electron identification capability and the knowledge of the background sources

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[5] The 4 σ discovery level is defined by the 1.0–(6.3×10^{-5}) CL upper-limit of the Poissonian with mean value corresponding to the expected number of background events.

will have to be confirmed by future test measurements.

Emulsion and scanning

Because of the low background level at the Gran Sasso and due to the fact that modern automatic scanning devices do not require emulsion with high "grain" densities (sensitivity), diluted emulsion can be used in OPERA. About 15 (25) ton of emulsion are needed with a density of silver bromide a factor three (two) lower than in CHORUS. Further, recent studies in Japan have shown that thin diluted emulsion sheets (unlike thick emulsion) can be processed regaining a sensitivity comparable to the one achieved in CHORUS. Contacts with producers have been established with the aim of obtaining good quality emulsion-gel within a reasonable period and at an acceptable cost. Tests will be performed jointly with them.

An important issue is the preparation of the emulsion before the exposure, *i.e.* pouring and assembling into emulsion sheets. We are studying solutions based on an automated laboratory, possibly operated by the gel producers. Another possibility is to use emulsion sheets similar to those employed for X-ray photographic-films, with adequate performance and substantial cost reduction with respect to present nuclear emulsion. Prototype films, which already exhibit good performance, have been recently tested by the Collaboration.

For the four years' run of the "realistic" scheme, the total number of events to be scanned is about 10000, which is much smaller than in CHORUS. However, in OPERA the scanning procedure is more time consuming: the electronic detectors locate events rather than individual tracks. Several cm^2 of the most downstream ES in the brick are scanned in correspondence with the detected interaction ("general" scanning) and all the found track segments are measured. These are then extrapolated and searched for in the upstream ESs, until the event vertex is reached ("scan-back" procedure). We can estimate a time of a few $\mathrm{hours/cm}^2$ for the general scanning using present generation automatic microscopes available in the Collaboration. The R&D undertaken by several groups of OPERA aims at a substantial increase of the scanning speed by employing hardware and software systems matching the scanning requirements.

Given the small rate of events (of the order of 10 per day) the emulsion analysis can be conducted "quasi" on-line. One can periodically remove (and possibly replace) those target bricks where the event vertex occurred and perform the emulsion scanning. This scheme allows an on-line physics analysis which diminuishes the relevance of the emulsion fading, thereby allowing a long running period. We observe that the number of bricks to be dismounted after one year of running (~ 2500) is small compared to the total number of ~ 100000.

Tests on prototypes

We have recently constructed prototype target-bricks by employing different plate materials (stainless steel, stainless steel/lead sandwich and nickel-plated lead), emulsion sheet thicknesses and types of spacers. The bricks were exposed to the muon flux associated to the CERN SPS neutrino beam and, at the same time, to the high energy muons of the test beam X7, which have a distinctive angular distribution. For some of the tests, the muon tracks could be selected in momentum, thanks to the measurement done with the downstream CHORUS spectrometer. The analysis of the emulsion is underway. The results of the tests will allow us to study, in particular, the angular resolution achievable in OPERA. The latter quantity defines the minimum detectable kink angle, which has direct implications for the signal detection efficiency.

A more thorough test programme is foreseen for the next year. It implies pion and electron beams exposure of modules made up of several bricks followed by electronic detectors. In such a way, the event and kink finding efficiency will be studied, by simulating decays through pion interactions. We will also test the electron identification capability by the ES and the momentum determination by means of multiple scattering measurement in the target bricks. Electronic detector prototypes will also be tested and studied, together with engineering solutions related to the construction of the apparatus.

Cost estimate

We have performed a first evaluation of the cost of the experiment. The cost estimates of active detectors are based on experience from a number of recent experiments. However, in some areas costing is based on conceptual engineering design: for example, in the case of lead/emulsion bricks. The total cost of the OPERA detector amounts to 48 MCHF. A breakdown is given in Table 4.

Table 4: Cost estimates (in MCHF)

item	cost
support structures: external detector support; support for supermodules planes	**1.5**
bricks: lead/inox sheets, surface passivation, spacers	**8.0**
robotics and automation: automatic assembly of bricks; automatic assembly of modules in situ	**1.8**
emulsion: including handling & laboratory	**27.0**
target detectors: scintillator and fibers, PMs, r/o electronics	**4.2**
magnetized iron: steel plates, coils, service	**1.2**
muon system instrumentation: muon tracking stations scintillators & fibers, PMs, r/o electronics	**2.5**
site preparation: cavern outfitting & infrastructures	**1.0**
data acquisition and control	**0.8**
GRAND TOTAL:	**48.0**

The experiment is planned to be ready for a first technical neutrino run in late 2003. Early physics results could come after the first year of data taking, thanks to the “quasi” on-line emulsion analysis.

Outlook

The study of the experiment proceeds with the aim of being ready to submit a proposal in the course of next year. With respect to the LoI [7], the target mass is increased to about 800 ton with a modular structure. An additional improvement in the sensitivity comes from the new NGS beam design, well suited for a $\nu_\mu \leftrightarrow \nu_\tau$ appearance search. In parallel, the potential background sources are being studied and the merits of the direct observation of the τ decay in the emulsion are confirmed.

The general layout of the OPERA detector and the characteristics of its components are being investigated, also by interaction with industry. The emulsion procurement, handling and scanning are among the priorities. Automation of the target brick assembly as well as the realization of the electronic detectors are other areas of collaboration with industry. Prototype bricks have been constructed and exposed to muon beams. A next generation of tests is planned.

In the hypothesis of the NGS "realistic" running scheme, the sensitivity of OPERA reaches $\Delta m^2 \sim 1 \times 10^{-3}$ eV^2. This covers the oscillation parameter region allowed by a global fit of the atmospheric neutrino data from the Super Kamiokande experiment. For solar neutrinos, global analyses of all experimental data are currently used to constrain the oscillation parameters beyond what can be inferred from single measurements. More work along this line is highly worthwhile for future, waiting for new atmospheric data and for the results from the long baseline K2K experiment. A positive result from OPERA would identify unambiguously the source of the oscillation mechanism. However, even a negative search would effectively contribute to the clarification of the scenario, *e.g.* giving support to the existence of a sterile neutrino.

A remark may be made on a possible extrapolation of the OPERA performance. The sensitivity of the experiment is not limited by background and one could contemplate a 50% statistics increase (2.5×10^{20} pot) over the "realistic" running scheme, achievable through a longer run, a dedicated operation mode of the SPS and/or improved accelerator performance. In the case of a positive search, the 4 σ statistical significance of ~ 5 τ events would then translate to $\Delta m^2 = 1.5 \times 10^{-3}$ eV^2.

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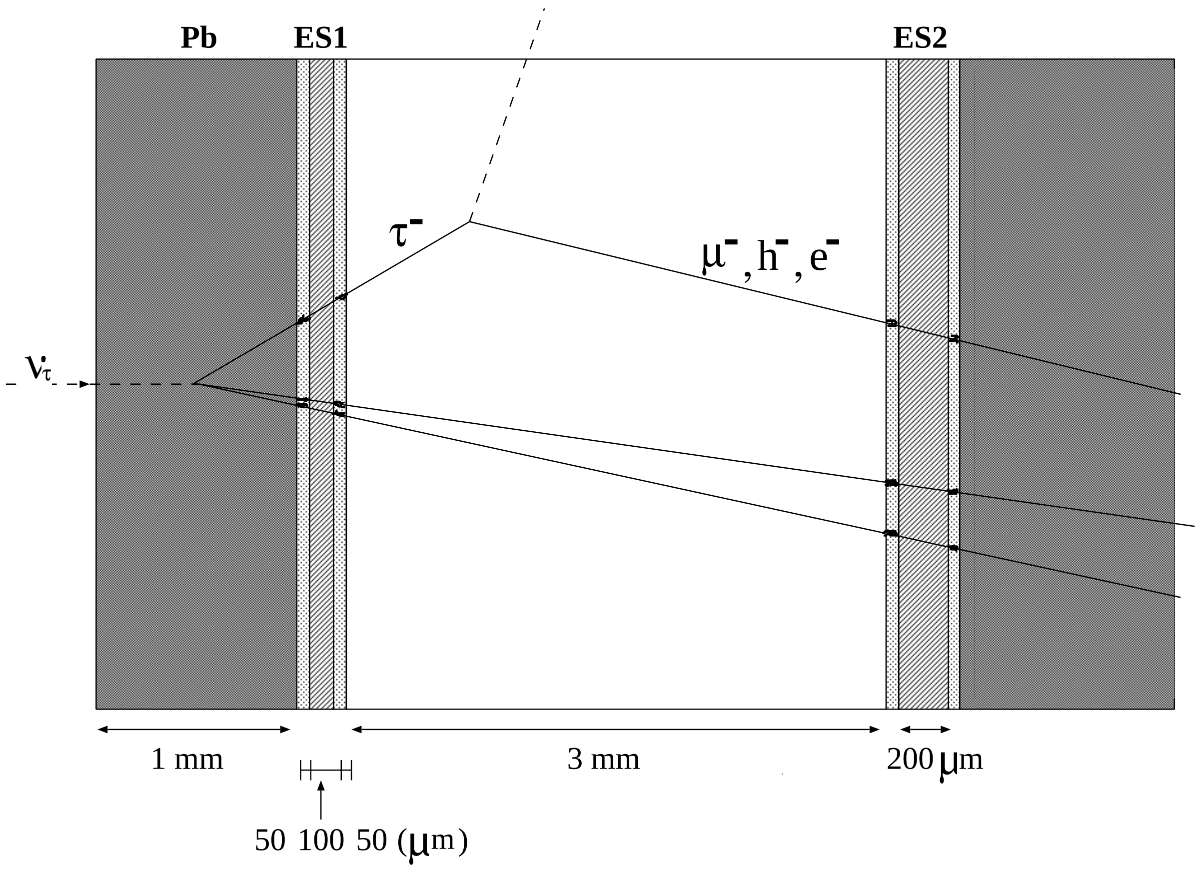

Figure 1: Schematic structure of the OPERA target. The τ decay kink is directly reconstructed in space by using four track segments in the emulsion sheets ES1 and ES2.

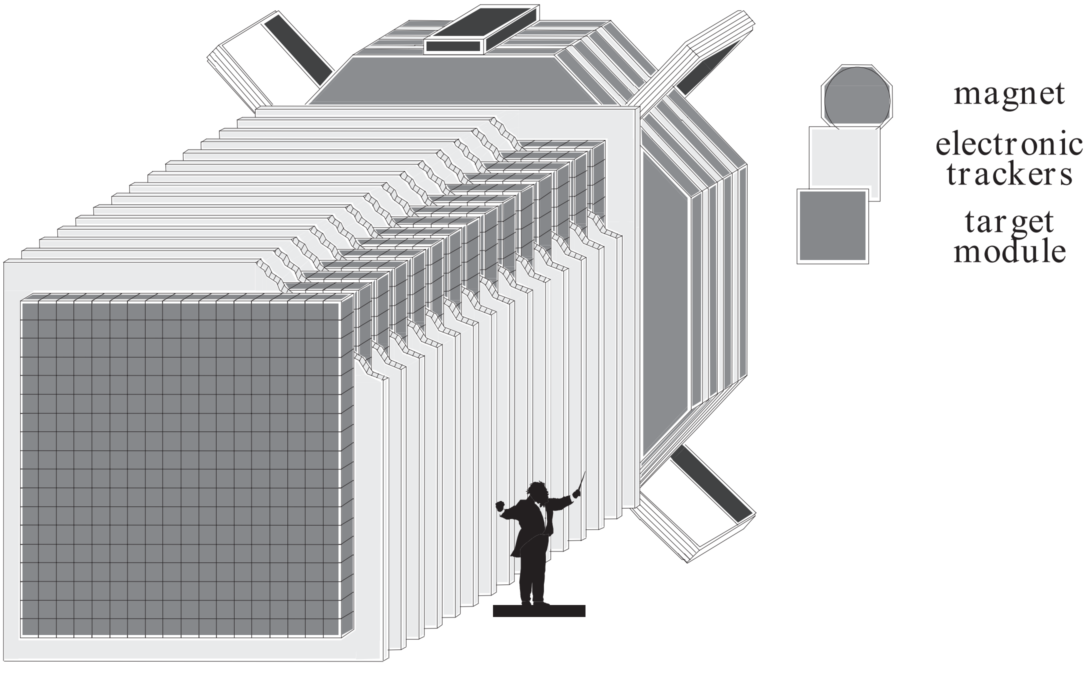

Figure 2: The concept of the OPERA detector supermodule.

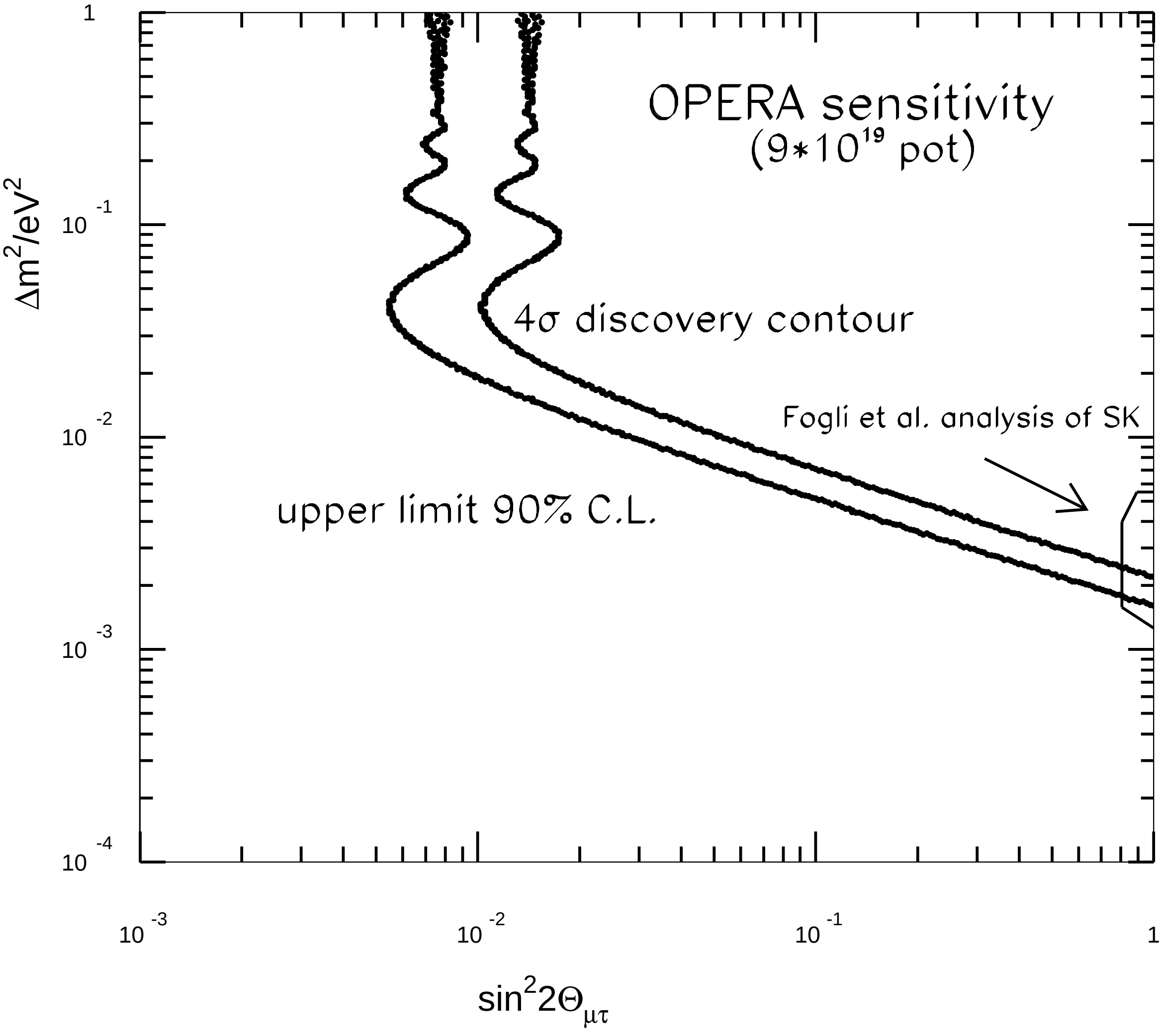

Figure 3: Sensitivity of OPERA in the search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation for the "baseline" running scheme. The 90% CL limits is plotted together with the 4 σ discovery contour. The region indicated by the analysis of Fogli et al. [15] of the Super Kamiokande data is also shown.

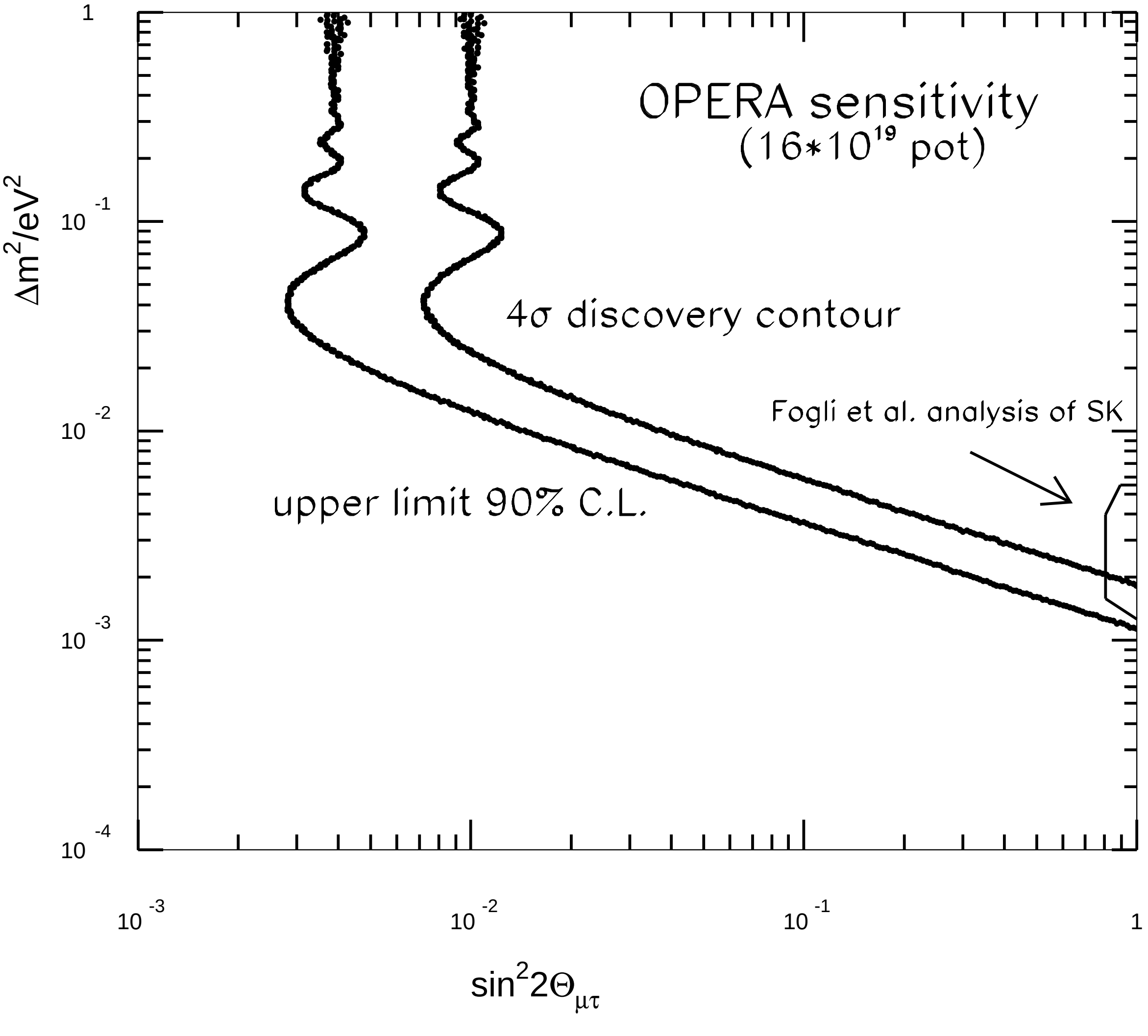

Figure 4: Sensitivity of OPERA in the search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation for the "realistic" running scheme. The 90% CL limits is plotted together with the 4 σ discovery contour. The region indicated by the analysis of Fogli et al. [15] of the Super Kamiokande data is also shown.