The OPERA experiment at Gran Sasso

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OPERA (Oscillation Project with Emulsion-tRacking Apparatus) is a long-baseline experiment to search for $\nu_\mu \to \nu_\tau$ oscillations in the Gran Sasso laboratory. It will study the interactions of 20 GeV neutrinos produced at CERN to search for neutrino flavour oscillation over a distance of about 730 Km. The OPERA detector is designed to unambiguously observe the appearance of ν_τ in a pure ν_μ beam. The detector is based on a massive lead/nuclear emulsion target. Nuclear emulsions are exploited for the direct observation of the decay of the τ lepton, produced in ν_τ charged-current interactions. The discovery potential of OPERA is ultimately due to a very low background level and could therefore play a decisive role in the clarification of the experimental scenario.

1. Introduction

The discovery of neutrino oscillations represents today the most powerful and elegant way to establish the non zero mass of the neutrino and a non vanishing mixing matrix between weak eigenstates in the leptonic sector [1].

Recent results on atmospheric neutrinos from the SuperKamiokande experiment seems to indicate that ν_μ produced by cosmic rays in the atmosphere could oscillate to a different flavour [2]. SuperKamiokande observed that ν_μ induced charged-current events in both sub-Gev and multi-Gev samples were fewer than the expectation by 40%; moreover the zenith angle distribution of those muons showed a strong up-down asymmetry, while electrons of similar energies had a symmetric zenith angle distribution. Muon neutrinos seems thus to oscillate in a different flavour while traversing the full earth diameter. This oscillation could be either due to $\nu_\mu \to \nu_\tau$ or to $\nu_\mu \to \nu_{\rm s}$ non vanishing mixing, if the "sterile" neutrino hypothesis is taken into account. It seems in fact very unlikely that $\nu_\mu \to \nu_{\rm e}$ oscillation could be relevant in a region already excluded by the CHOOZ experiment at 90% C.L. [3].

When interpreted as due to $\nu_\mu \to \nu_\tau$ oscillation, the SuperKamiokande results focus the attention at $\Delta {\rm m}^2_{\mu\tau} = 10^{-3} \div 10^{-2}$ eV^2 and large mixing angle. In the two flavour mixing scheme the oscillation probability is given by $P_{\mu\tau} = \sin^2 2\theta_{\mu\tau} \cdot \sin^2(1.27\Delta{\rm m}^2_{\mu\tau}{\rm L}/{\rm E}_\nu)$, where the squared mass difference is expressed in eV^2, L in kilometers and $\rm E_\nu$ in GeV. The best way to explore the low $\Delta{\rm m}^2_{\mu\tau}$ region pointed out by SuperKamiokande is therefore an appearance experiment (which constraints $\rm E_\nu$ above the τ production threshold) with a $\rm L/E_\nu$ ratio of the order of $10^2 \div 10^3$ (forcing the experiment to be "long-baseline").

2. Cern Neutrino beam to Gran Sasso

A long-baseline neutrino beam pointed to the Gran Sasso laboratory in Italy is under way of approval at CERN [4]. The SPS primary proton beam of 400 GeV is focused onto a graphite target, producing secondary mesons. Among them, high momenta π^+ and K^+ are selected and focused towards the Gran Sasso Laboratory by a two-stage magnet system made of a horn and a reflector. Neutrinos are produced in a 900 m length vacuum tunnel by the decay in flight of π^+ and K^+. The distance between the production point at CERN and Gran Sasso Laboratory in Italy is about 730 Km.

The neutrino beam contains predominantly muon neutrinos with an average energy of 20 GeV, and a contamination of $\overline{\nu}_\mu$, ν_e and $\overline{\nu}_e$ at the level of 10^{-2}. The estimated ν_τ background is

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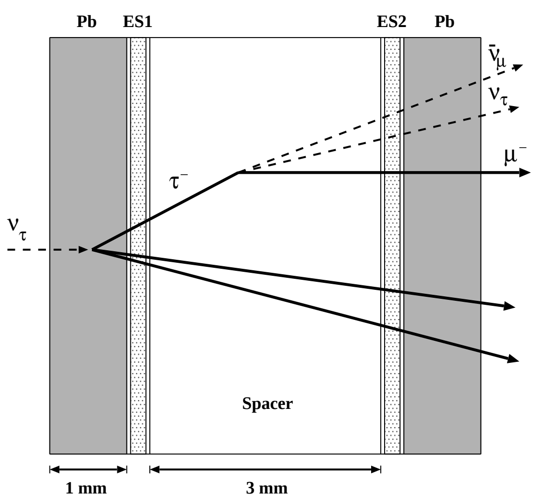

Figure 1. Schematic view of the OPERA cell. The decay of the τ lepton in the spacer is identified by the track segments reconstructed in the emulsion sheets before (ES1) and after (ES2) the 3 mm gap.

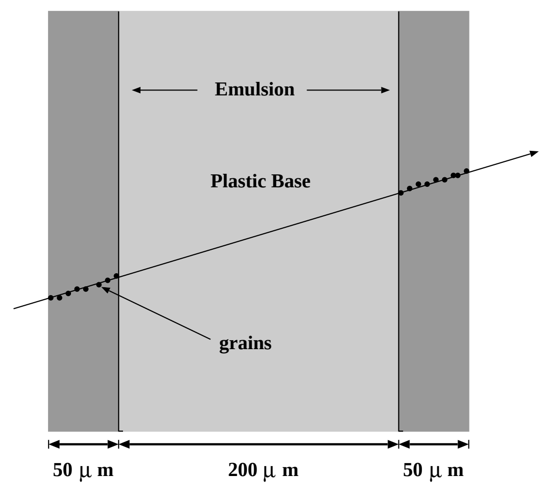

Figure 2. Structure of an OPERA emulsion sheet (ES). Also shown are Ag grains along a ionizing track obtained after emulsion development. The grains are not to scale and possible emulsion distortion effects are not displayed.

obtained using the procedure described in ref. [5]. On a lead/emulsion detector placed at a distance of 730 Km from the neutrino source a total number of 1.5×10^{-6} ν_τ charged-current interactions per ν_μ charged-current interaction are expected.

The proton intensity on the target will be of about 4×10^{19} pot/year. The expected neutrino flux at the Gran Sasso laboratory would produce about 2000 charged-current ν_μ events per kton/year. The expected yield of interacting ν_τ is 2.8 events/10^{19}pot/kton, computed for $\Delta m^2_{\mu\tau} = 2.5 \times 10^{-3}$ eV^2 at full mixing. These estimates are to be considered very conservative since further improvements to enhance the neutrino beam performance and the overall ν_τ yield are actually under study.

3. The OPERA detector

The OPERA experiment [6] is designed to detect $\nu_\mu \to \nu_\tau$ oscillation by directly tagging the τ decay using nuclear emulsion trackers.

The OPERA concept is an evolution of the ECC technique [7]. The new 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. This results in a substantial background reduction.

Charged particles trajectories are reconstructed by means of two track segments in each ES, before and after the decay gap. Emulsion sheet excellent spatial resolution provide an angle measurement accuracy of about 4 mrad on each ES, and allows to detect kink angles in the range $20 \div 500$ mrad with an efficiency well above 80%. To avoid fake kinks due to primary particle re-interaction in the decay gap the spacer consists of very low density material.

The present design of the OPERA detector, whose optimization is underway, is a lead/emulsion target subdivided into "bricks". The brick, weighing about 8 kg, has dimensions orthogonal to the beam direction of 15×15 cm and a thickness of about 14 cm ($\sim 5X_o$) along

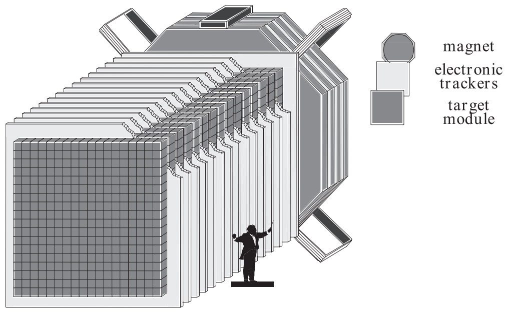

Figure 3. The OPERA supermodule actually comprises 16 modules and a magnetized muon spectrometer. The transverse size of the supermodule is of about 6.5 m. In this configuration the OPERA detector consists of 2 adjacent columns of 5 supermodules. The length of the detector is about 35 m.

the beam. Each brick 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 Figure 1. Both emulsion sheet consists of a 50 μm nuclear emulsion layer deposed on both sides of a 200 μm thick plastic base, as shown in Figure 2.

A matrix of adjacent bricks, arranged in a plane structure and followed by a plane of electronic detectors, forms a target "module". Electronic detectors are needed to identify the brick where each interaction took place and to guide the scanning procedure. The performance requirements for the electronic detectors are of about 1 cm space accuracy, high efficiency and long-term reliability. The very large total area to be covered (about 5000 m^2) restricts the choice to mature technologies such as scintillator strips or RPC.

The modularity of the target allows to conceive a total target mass of about 800 ton, suited to meet the physics goal of the experiment. The target structure also permits the removal of those bricks where an interaction tool place and to analyze their emulsion sheets soon after. In the present design a module is composed by a wall of 25 × 25 bricks, about 5 m wide. The "supermodule" is made by 16 of these modules followed by a muon spectrometer, needed to identify the muon charge and to measure its momentum. The typical mass of a supermodule is about 80 tons. A drawing of a supermodule is shown in Figure 3.

4. Event reconstruction and background

The excellent angle and spatial resolution of the emulsion make it possible to clearly reconstruct the "kink" produced by the τ decay. All 1-prong τ decay channels can be studied, resulting in a total visible branching ratio of about 86%; when folded with beam spectrum and detection efficiency this results in an overall $\epsilon_\tau \sim 30\%$ (at $\Delta m^2_{\mu\tau} \sim 2.5 \times 10^{-3}$ eV^2). This high efficiency, when compared to other experiments that aim at $\nu_\mu \to \nu_\tau$ oscillation detection by appearance, allows the OPERA experiment to be relatively "low mass", while still providing adequate sensitivity to neutrino oscillation.

The background evaluation has been performed using a full Monte-Carlo simulation, including beam features, physics processes and detector characteristics. The expected background sources for τ decays are mainly due to 1-prong decay of charmed particles produced in neutrino interactions, since charmed mesons have mass and lifetimes similar to those of the τ. Charmed particles are produced in charged-current and neutral current neutrino interactions through the reactions: $\nu_\mu + N \to c + \mu + X$, $\nu_\mu + N \to c + \bar{c} + \mu + X$, $\nu + N \to c + \bar{c} + \nu + X$. These processes may constitute a background to the oscillation signal if one fails to detect the primary muon or the charm partner. Other background events are expected to arise from π and K decay in the gap and from hadron re-interaction in the spacer.

In the realistic running scheme mentioned in the following section and for the three 1-prong τ decay channels (μ^-, h^- and e^-) the OPERA experiment expects about 0.15 background events due to charm production, 0.2 events due to π and K decay and 0.55 events due to hadron reinteraction in the spacer. This background is easily reduced applying a cut on the transverse momentum of the decay particle and a kinematical

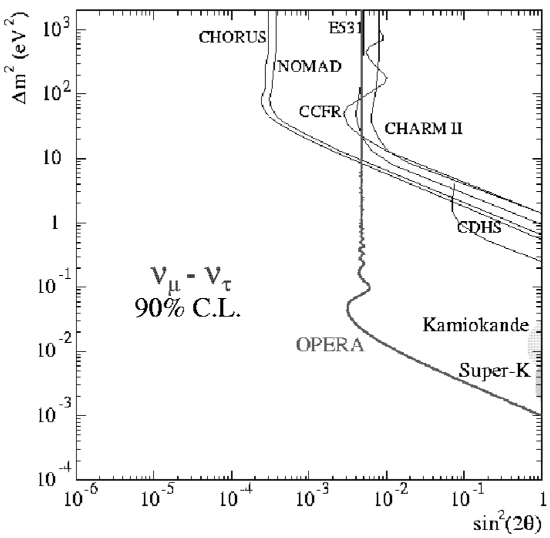

Figure 4. Region in the $\nu_\mu \to \nu_\tau$ oscillation plane excluded at 90%C.L. in case of no signal events found. Also shown is the SuperKamiokande allowed region.

analysis of the event topology at vertex. Both methods rely on the measure of the τ lepton direction before the decay. An overall background of 0.4 events is left. The OPERA experiment is thus practically background free.

5. Sensitivity to $\nu_\mu \to \nu_\tau$ oscillation

The OPERA experiment is designed for discovery. A 10 supermodules setup corresponds to a target mass of about 800 ton. Assuming a data taking period of 4 years, a total of 1.6×10^{20} pot could be easily achieved; such intensity would produce in the OPERA detector about 10000 neutrino interaction events. Given the τ yield mentioned before and assuming that $\nu_\mu \to \nu_\tau$ oscillation occurs at a large mixing angle and $\Delta m^2_{\mu\tau} \sim 3.5 \times 10^{-3}$ eV^2, a total of 20 τ events completely reconstructed in the detector is expected.

In case of no τ event candidates found OPERA could easily cover the region allowed by the SuperKamiokande experiment in the $\nu_\mu \to \nu_\tau$ plane. An upper limit of $\Delta m^2_{\mu\tau} < 1 \times 10^{-3}$ eV^2 at a large mixing angle could be established at 90% C.L., as shown in Figure 4.

6. Conclusions

The OPERA project is motivated by the latest SuperKamiokande results on the detection of ν_μ oscillation in atmospheric neutrino data. Due to its excellent characteristics the OPERA detector could give an ultimate answer to the possibility of a $\nu_\mu \to \nu_\tau$ oscillation scenario. Being a zero background experiment OPERA could establish neutrino oscillation even on a few event basis. Further improvements on the neutrino beam line and on the detector design are expected to further increase the experiment sensitivity [8].

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