OPERA, AN APPEARANCE EXPERIMENT TO SEARCH FOR NEUTRINO OSCILLATIONS IN THE CNGS BEAM*

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The OPERA experiment is dedicated to the direct observation of ν_τ neutrinos in the long baseline ν_μ CNGS beam. Here, a general description of the OPERA detector and its physics performance is presented, the preliminary test results with underground cosmic muons are shown as well.

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1. Introduction

The deficit of atmospheric ν_μ as showed by the zenith angle and L/E distributions observed by Super-Kamiokande (SK) [1] provides a very strong hint in favor of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The long baseline projects in Japan [2] and in the USA [3] use accelerator neutrinos to investigate the disappearance of ν_μ with a controllable beam. In Europe, the CNGS project (CERN Neutrinos to Gran Sasso) with the OPERA experiment will study the appearance of ν_τ in the purely ν_μ beam, over a long baseline ($L = 732$ km). OPERA (Oscillation Project with Emulsion-tRacking Apparatus) [5] will search for τ leptons produced in ν_τCC interactions, using nuclear emulsions for the very precise tracking and electronic detectors to locate events.

2. The CNGS beam

The CNGS beam [4] of ν_μ neutrinos will be produced with the 400 GeV protons extracted from the SPS at CERN. After proton interactions on the

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graphite target, a system of magnetic lenses (the horn and the reflector) will select from secondary particles the high energy π^+ and K^+s. Pions and kaons will be then directed towards a decay tunnel, producing the neutrino beam. A contamination of about 2% $\bar{\nu_\mu}$, 0.8% $\bar{\nu_e}$ and 0.05% ν_e is expected in the beam, with a negligible ν_τ contribution. The CNGS is expected to deliver 4.5×10^{19} protons on target (pot) per year, assuming 200 days of running. The ν_μ flux will have an average energy of 17.4 GeV and in the 1.8 ktons OPERA detector will produce 23k ν_μNC and 7k ν_μCC interactions, after 5 years. Possible improvements to the proton beam line would increase the beam intensity to 6.7×10^{19} pot. The construction of the CNGS is on schedule and first neutrinos will be sent to Gran Sasso around mid 2006.

3. The OPERA detector

The OPERA detection technique is based on the concept of the Emulsion Cloud Chamber (ECC), already used by the DONUT experiment [6]. The ECC consists of series of emulsion films (two 50 μm thick emulsion layers, put on either side of a 200 μm thick plastic base) interleaved with 1 mm thick lead plates (figure 1). This solution combines the high precision tracking in emulsions with the high target mass for ν interactions. The thickness of the emulsion layer corresponds to 15–20 film grains and its spatial resolution is about 0.3 μm (readout accuracy). The basic detector unit, an ECC brick, is obtained by stacking 56 lead plates with 57 emulsion films. Dimensions of the ECC brick are $12.7 \times 10.2 \times 7.5$ cm and its mass is 8.3 kg. In order to reach 1.8 kton target mass, 206336 bricks will be installed in the detector.

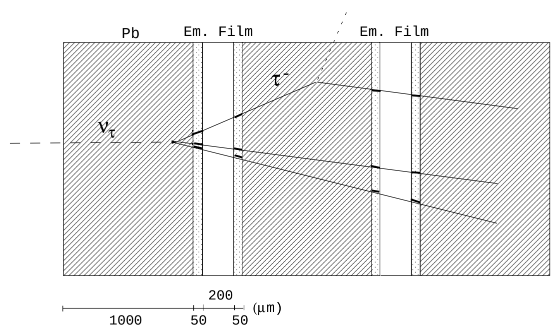

Fig. 1. The schematic structure of an ECC cell with the ν_τCC interaction.

Figure 2 shows the layout of the OPERA detector. It consists of two identical parts called Super Modules, with a target section and a muon spectrometer. The target section consists of 31 modules, each with a target wall (64 rows of 52 bricks) followed by an electronic Target Tracker (TT). The TT is composed of vertical and horizontal planes, each with 256 plastic scintillator strips, 6.7 m long and 2.5 cm wide. Strips are instrumented on both ends with a WLS fibers, connected to 64 channel multi-anode PMTs. The main goal of the electronic detector is to provide a trigger for ν interactions and to locate the brick where the event occurs.

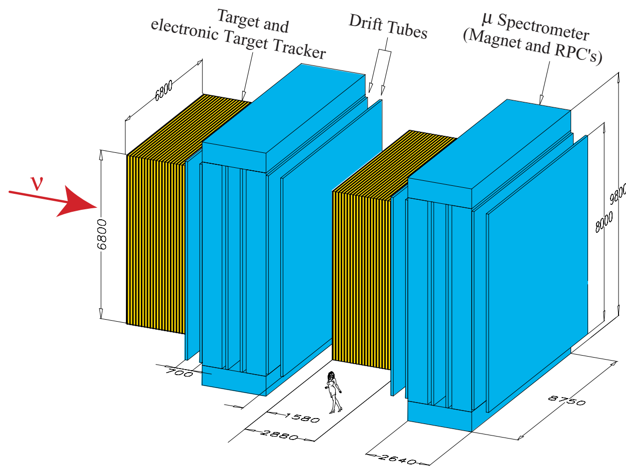

Fig. 2. The schematic view of the OPERA detector.

The muon spectrometer consists of a dipole magnet ($B = 1.55$ T) with two iron arms of transverse dimensions 8.75×8 m. Each arm is made of 12 iron planes 5 cm thick, interleaved with 11 planes of Resistive Plate Chambers (RPC's) 7 mm thick. Each plane consists of 7 rows of 3 RPCs and is digitally read-out by the vertical and horizontal panels of 2.6 and 3.4 cm wide pickup cooper strips. In addition, magnet arms are interleaved with 3 pairs of high precision trackers formed by planes of 8 m long vertical Drift Tubes. Their intrinsic resolution in the bending direction is 0.5 mm. The spectrometer system allows the detection of through going muons, mainly to tag the $\tau \to \mu$ decay channel and to reject the charm background.

Given the trigger from electronic detectors, bricks will be removed from the sides of the target wall using dedicated robotics (Beam Manipulator System). After the development, emulsion layers will be send to automatic high scanning speed (> 20 cm^2/h) stations for the event reconstruction.

The installation of the OPERA detector in Hall C of LNGS started in May 2003. By now, both spectrometers are completed, together with the drift tubes and the target section in SM1. About 80% of nuclear emulsions have been produced by the Fuji company and half of them already shipped to LNGS. The filling of SM1 with ECC bricks will be finished by the end of July 2006. The filling of SM2 will proceed in pararell with data taking in SM1.

4. The OPERA physics performance

The $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are identified by means of ν_τCC interactions in the target, with the τ lepton in the final state. The investigated τ decay channels are $\tau \to e$, $\tau \to \mu$ and $\tau \to$ hadrons. If the τ is produced in one lead plate it will decay either in the same plate (short decays) or further downstream (long decays). "Long decays" are selected by searching for the kink angle between the τ and its daughter track (figure 1). "Short decays" are selected based on the impact parameter of the τ daughter track w.r.t. the interaction vertex (IP $>$ 5–20 μm). After the topological selection additional kinematic cuts are applied in order to improve the signal to background ratio. Contributing background processes are charm decays, the large angle muon scattering and hadron interactions. The total τ detection efficiency, including branching ratios, amounts to 9.1%.

Table I shows the expected number of τ events after 5 years of running with the nominal CNGS intensity. The values of Δm^2 correspond to the best fit and the boundaries of the SK latest 90 % C.L. allowed region (L/E analysis), at full mixing. For the best SK fit OPERA expects to observe 13 τ decays with the background of 1 event. This translates into a 4σ discovery probability of 95%. The discovery potential for the lowest and highest allowed Δm^2 amounts to 70% and 100%, respectively. In case no signal is observed, OPERA will exclude the region shown in figure 3.

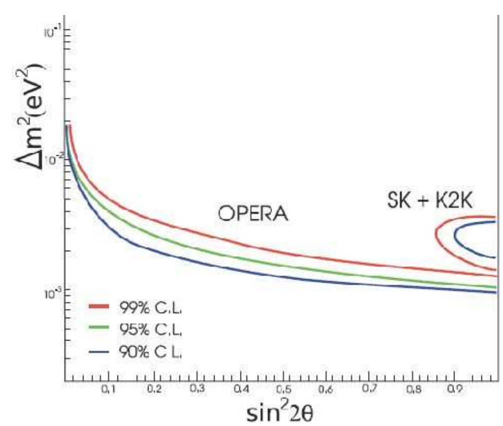

Fig. 3. The OPERA sensitivity to $\nu_\mu \to \mu_\tau$ oscillations after 5 years of CNGS running, together with the region allowed by the combined SK [1] and K2K [2] data.

OPERA will be also sensitive to $\nu_\mu \to \nu_e$ oscillations [8] and may improve the present CHOOZ [7] limit on $\sin^2 2\theta_{13}$ from 0.14 to 0.06.

TABLE I

The number of signal and background events as a function of Δm^2. Numbers in brackets correspond to the CNGS beam intensity upgrade ($\times 1.5$).

$\Delta m^2 =$	1.9×10^{-3}	2.4×10^{-3}	3.0×10^{-3}	bkgd
	8.0 (12.1)	12.8 (19.2)	19.9 (29.9)	1.0 (1.5)

5. Test results with underground cosmic muons

After the installation of spectrometers at LNGS the last 4 planes of the first spectrometer were tested ($\sim 20\%$ of RPCs) in order to check the RPC performance in underground conditions. Tests allowed also first OPERA investigations of muons under the Gran Sasso mountain. The corresponding see-level energy spectrum of these muons is $E_\mu > 1$ TeV [10].

Measurements were performed with no magnetic field in the spectrometer, using self-triggering electronics boards of the former MACRO experiment. Muon tracks were selected by requiring the coincidence of signals in three planes (for additional fourth plane efficiency studies). In the sample collected for 62 hours, 1307 single-muon, 24 di-muons, 3 four-muons and 1 six-muon events have been found after visual scanning. The number of single muons corresponds to the rate of 21.0 ± 0.6 μ/h.

By requiring a very clean track topology (one horizontal and one vertical strip cluster per plane, figure 4) 973 muons and a rate of 15.6 ± 0.5 μ/h has been measured, in very good agreement with the Monte Carlo prediction, 15.2 ± 0.3 μ/h. The MC (developed for the MACRO experiment) simulates the underground muon flux based on the empirical formula for vertical muon intensity [9] modified to account for the Gran Sasso rock structure [10]. Selected tracks were fitted in each view with a straight line. Figure 4 shows the residuals of the fit, well described by the MC with the detailed GEANT simulation of the OPERA detector. Angles related to the slope of the straight line ($a = \tan\theta$) are shown in figure 5. Apart from the good agreement between the data and the MC (absolute normalisation), the effect of the non-uniform rock distribution around the laboratory can be observed.

The MC simulation predicts the muon rate of 35 μ/h in the entire spectrometer. This corresponds to a sample of about 3×10^6 muons that can be detected in both OPERA spectrometers after 5 years of smooth running.

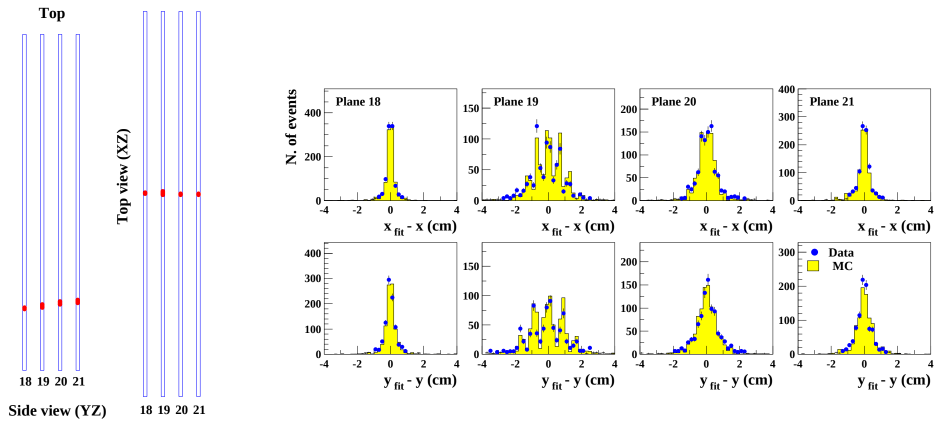

Fig. 4. An example of a single μ event observed with the last 4 spectrometer planes (left). Residuals of the straight line fit to deposits in planes 18, 20, 21 (right).

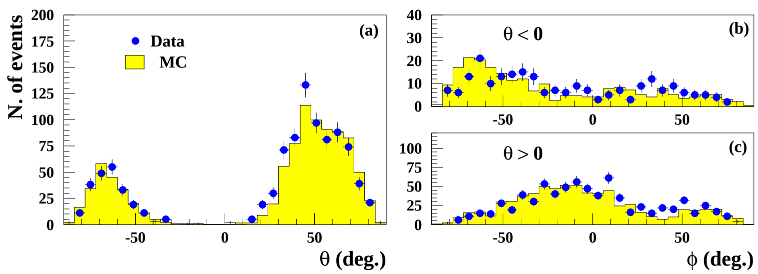

Fig. 5. Angular distributions of underground muons, measured with 4 spectrometer planes. Angles correspond to the slopes of the muon track (a) in the vertical and (b),(c) horizontal projections. $\theta = 0$ corresponds to the zenith direction.

6. Summary and conclusions

The CNGS will enter in operation around mid 2006. The OPERA experiment aims at observing the ν_τ appearance with an excellent signal to background ratio. This would provide a convincing proof of the oscillation mechanism.

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