The OPERA long baseline neutrino oscillation experiment

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Abstract. OPERA is a long baseline neutrino oscillation experiment designed to observe the appearance of $\nu_\tau$ in a pure $\nu_\mu$ beam in the parameter space indicated by the atmospheric neutrinos oscillation signal. The detector is situated in the underground LNGS laboratory under 3 800 water meter equivalent at a distance of 730 km from CERN where the CNGS neutrino beam to which it is exposed originates. It consists of two identical 0.68 kilotons lead/nuclear emulsion targets, each instrumented with a tracking device and complemented by a muon spectrometer. The concept and the status of the detector are described and the first results obtained with cosmic rays and during two weeks of beam commissioning in 2006 are reported.

1. Introduction
The measurements of neutrinos fluxes from all usable sources, the Sun, the Earth atmosphere, the accelerator beams and the nuclear reactors, form a coherent set of compelling experimental evidences for oscillation between neutrino flavours. This, in turn, implies that neutrinos have non-degenerate masses and that their mass and weak interaction or flavour eigenstates mix [1]. In the 3-neutrino flavours mixing scheme in vacuum, the probability for a neutrino to disappear into another flavour or to survive during its propagation is the superposition of oscillatory terms whose amplitudes are defined by the elements of the unitary mixing matrix and whose wavelength is proportional to the corresponding squared mass differences between pairs of mass eigenstates and to the ratio of the propagation distance $L$ to the neutrino energy $E$. When propagation occurs in matter, additional terms appear in the oscillation probability. They are caused by the differences in forward elastic cross-sections with matter constituents between the $\nu_e$, the $\nu_\mu/\nu_\tau$ and possible sterile neutrinos. Matter effects are negligible in the particular context of the OPERA experiment

The strong energy dependent deficit in the solar $\nu_e$ flux observed since several decades is well understood in terms of $\nu_e$ disappearance into an undetermined superposition of the other two active neutrino flavours [2], the total neutrino flux measured in the NC interaction channel [3] being in agreement with the Standard Solar Model expectation [4]. This scenario has been further supported by the evidence of a spectral distortion in long baseline nuclear reactors flux measurements [5].

Similarly, a strong energy and distance dependent deficit in the flux of $\nu_\mu$ produced by cosmic rays interactions in the atmosphere has been observed since two decades [6] and evidence has been obtained for an oscillatory signature in the $L/E$ spectrum [20]. No such deficit is observed in the $\nu_e$ flux, thus implying that $\nu_\mu/\nu_e$ cannot be the dominant oscillation channel. This is further supported by

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the agreement between short baselines nuclear reactors flux measurements with expectations [7]. The favoured oscillation channel is $\nu_\mu - \nu_\tau$, the pure oscillation of $\nu_\mu$ into sterile neutrinos being excluded [8]. Accelerator experiments have confirmed the oscillation scenario by measuring the $\nu_\mu$ flux deficit at large distances [9] and its energy dependence [10].

The coherent picture emerging from all these observations is compatible with a full mixing between the $\nu_\mu$ and the $\nu_\tau$ and no $\nu_e$ content into the $\nu_3$, the squared mass differences between eigenstates being $\Delta m^2_{23} \approx 8.4 \times 10^{-5} \text{eV}^2$ and $\left| \Delta m^2_{13} \right| \approx \left| \Delta m^2_{23} \right| \approx 2.4 \times 10^{-3} \text{eV}^2$.

Still, none of these experiments yet has observed unambiguously the appearance of a new flavour in a neutrino flux by identifying the charged lepton produced in its charged current (CC) interaction with matter. The OPERA experiment precisely aims at identifying the $\tau$ produced in the CC interactions of $\nu_\tau$ appearing in a pure $\nu_\mu$ beam and thus confirming the preferred interpretation in the atmospheric sector by probing a similar domain of $L/E$.

2. The CNGS beam and the OPERA detector

The CERN CNGS $\nu_\mu$ beam was designed and optimized to maximize the number of CC interactions of $\nu_\tau$ produced by oscillation at the Gran Sasso LNGS underground laboratory, at 730 km from CERN, where the detector is placed. A 400 GeV proton beam is extracted from the CERN SPS in 10.5 $\mu$s short pulses with a design intensity of $2.4 \times 10^{13}$ protons on target (p.o.t.) per pulse. The nominal integrated beam intensity is $4.5 \times 10^{19}$ p.o.t. per year [11]. The average neutrino energy at the LNGS location is 17 GeV. The average $L/E$ ratio is thus 43 km/GeV, about 10% of the value maximizing the oscillation probability for $\Delta m^2_{23}$. The $\nu_\mu$ contamination is around 4%, the $\nu_e/\bar{\nu}_e$ contamination is lower than 1% and the number of prompt $\tau$ is negligible.

The OPERA detector is made of two identical super–modules consisting of a 0.68-kton instrumented target followed by a $10 \times 8$ m$^2$ dipolar magnetic muon spectrometer. One target is the repetition of 29 6.7 × 6.7 m$^2$ units each including a proper target wall followed by a target tracker wall. A target wall is an assembly of 42 horizontal trays, each of which is loaded with 64 bricks of 8.3 kg each. A brick is made of 56 lead sheets, 1 mm thick, providing the necessary mass, interleaved with 57 nuclear emulsion films that provide the necessary sub–micrometre spatial resolution and sub-milliradian angular resolution required to detect and separate unambiguously the production and decay vertices of the short-lived $\tau^-$ leptons produced in charged current $\nu_\tau$ interactions with the lead nuclei. This so-called Emulsion Cloud Chamber (ECC) technology has been used by the DONUT Collaboration to observe the first $\nu_\tau$ interactions [19].

Each Target Tracker (TT) wall consists of two planes of four adjacent modules each, one providing the vertical and the other the horizontal coordinates. A module is the juxtaposition of 64 6.3 m long, 10.6 mm thick and 26.3 mm wide polystyrene scintillator strips readout by wave length shifting fibres. These are connected at both ends to a 64-channel multianode PM tube [12]. The TT generates the trigger and provides the location of the brick in which the interaction has taken place.

Each muon spectrometer consists of a dipolar magnet made of two iron arms for a total weight of 990 ton [13]. The magnetic field intensity is 1.52 T. Planes of Resistive Plates Chambers (RPC) are inserted between the iron plates providing a coarse tracking inside the magnet, range measurement of the stopping particles and calorimetric information[14]. They consist of electrode plates made of 2 mm thick plastic laminate of high resistivity painted with graphite. Induced pulses are collected on two pickup planes made of copper strips, 26 mm wide vertically and 35 mm horizontally, glued on plastic foils placed on each side of the chambers.

The two arms of each magnet are interleaved with six fourfold layers of vertical planes of 8 m long drift-tubes with an outer diameter of 38 mm and a sense wire of 45 $\mu$m. They form the High Precision Tracker (HPT) that provides a spatial resolution of 300 $\mu$m in the bending plane to measure the muons momenta and determine the sign of their charge with high accuracy [15].
In order to solve ambiguities in the track reconstruction, each dipole magnet is complemented by an upstream RPC plane with two 42.6° crossed strip-layers. Finally, a detector made of glass RPC is placed in front of the first Super Module, acting as a veto for interactions occurring in the upstream material.

3. The emulsion scanning procedure.
The bricks in which neutrino interactions will be predicted to have occurred after reconstruction of the electronic detectors data, typically 25 per day, will be extracted on a regular base. The envelope loaded with two changeable sheets of emulsion (CS) that is glued on the rear face of each brick will be removed and the films analysed in order to validate the prediction and measure with very high resolution the positions and directions of tracks constituting the event. These data will serve as the starting values of the extrapolation procedure towards the exit face of the downstream film of the bricks. These will be disassembled, the films processed and the tracks followed from film to film back to the interaction vertex, the vicinity of which will be scanned for a topology compatible with the decay of a $\tau^-$ lepton. A battery of high speed, high resolution automatic microscopes have been developed for the purpose of this search [18].

The ECC technology also provides valuable information, based on ionization and multiple scattering measurements, on particle kinematics and identification at low energy complementing that obtained from the electronic detectors.

4. Performance of the electronic detectors with cosmic events and results of the first runs with the CNGS beam
Most electronic detectors have been commissioned already with the exception of two layers of drift tubes and the veto plane that will be completed during summer 2007. The efficiency of the target tracker exceeds 96% for all modules and averages at 99%. The low noise rate of 20 Hz per channel allows lowering the trigger threshold down to 1 photo-electron. Similarly, the efficiency of the RPC plates exceeds 90% and averages at 95%. The RMS of the hit residuals of the HPT before the final alignment is 500 $\mu$m. All these preliminary numbers have been obtained with atmospheric muons tracks that are mostly parallel to the detector planes; they are expected to improve for tracks associated to beam events.

A first 13-day run with the detector exposed to a low intensity beam started on 18 August 2006 providing a total luminosity of $7.6\times10^{17}$ p.o.t., equivalent to 5 days of running at nominal intensity [16]. A second run, foreseen in November was interrupted after only 25 hours due to a major water leak in the beam reflector magnet. A total of 319 interactions induced by beam neutrinos, mainly in the surrounding rock and the magnet iron, were recorded where about 300 were expected. The timing analysis of the events is summarised on figure 1. The left plot shows the time distribution of the events with respect to the start of the first of the two extractions per accelerator cycle. The plot to the right shows the time with respect to the beginning of the nearest extraction. The nominal time gap of 50 ms between extractions and the 10.5 $\mu$s duration of the extraction are retrieved. The expected number of events from the uniform cosmic rays background is $10^4$.

The angle with respect to horizontal of the single track-like events recorded during the same period is shown in Figure 2. By convention, it is positive for tracks entering the detector from the front, would they be up-going. At large angle, the agreement with the absolute predictions of a cosmic rays simulation [17] is excellent. The peak at small angle is populated by beam events. It has an average of $3.4\pm0.3^\circ$ in agreement with the 3.3$^\circ$ beam line angle.

The inset on figure 2 shows the angular distribution of the tracks in time with the beam which demonstrates the coherency between the independent timing and angle analyses.

The 10 ns hits time resolution of the TT allows distinguishing up-going from down-going tracks. Figure 3 shows the velocity distribution of particles registered during the beam period with the negative sign arbitrarily assigned to the down-going particles. The peak at positive velocity is due to particles associated to beam interactions. It is absent in similar plots taken when the beam is off.
Figure 1. Time distribution of the events recorded during the CNGS beam run with respect to the beginning of the first of the two extractions (left) and to the beginning of the nearest extraction (right).

Figure 2. Angle with respect to the horizontal of the track like events recorded during the CNGS beam run (dots). The histogram shows the prediction from a cosmic-ray simulation. The inset shows the angular distribution of the events in time with the beam.

Figure 3. Velocity of the track like events recorded during the CNGS beam run. By convention, up-going particles have a positive velocity.

5. Sensitivity to oscillation
At the nominal beam luminosity and with a target mass of 1.36 ktons, the expected number of identified ντ interactions after 5 years of running is 10.4 for $|\Delta m^2| \approx 2.4 \times 10^{-3} eV^2$ at full mixing.

The number of signal events scales with $|\Delta m^2|$. Background is caused mainly by charm decays, secondary hadron interactions and large angle scatterings of muons in the lead. The total background is expected to be as low as 0.8 events, the 4-σ discovery probability at this value of $|\Delta m^2|$ being 95%.

6. Near future prospects as conclusions
A period of three weeks of beam commissioning followed by three weeks of physics run at 70% of the nominal luminosity is due to start mid-September 2007. At that moment, the target will be filled with around 600 tons of bricks and will record about 180 neutrinos interactions, of which 10 with a charm decay mimicking the τ decay for the sake of verifying the ability of the emulsion scanning systems to locate such topologies. By May 2008, the OPERA target will be fully filled in due time to collect events from the CNGS beam expected to run at nominal intensity for a first 200-day period.
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