OPERA: LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT

M. GULER (for the OPERA Collaboration)
Physics Department, Middle East Technical University,
Ankara, TURKEY.

Abstract. - OPERA (Oscillation Project with Emulsion tRacking Apparatus) is a long baseline neutrino oscillation experiment which is designed to search for muon neutrino to tau neutrino oscillations in appearance mode. The OPERA detector is placed in the Gran Sasso underground laboratory, 730 km away from CERN, where neutrino beam (CNGS) is produced. The detector is a hybrid set-up which combines a lead/emulsion target with various electronic detectors. It consists of two identical Super Module each weighted 0.68 Kton. The concept of the search will be described and the first results obtained in 2007 and 2008 will be reported.

1. Introduction

There is now convincing evidence for neutrino oscillations from atmospheric and solar neutrino experiments. But all these measurements are based on disappearance of the original flavor or the ratio between charged-current and neutral-current ones. Indeed, solar neutrinos have not enough energy to produce charged leptons other than electrons while at the atmospheric neutrino scale the leading oscillation channel is $\nu_\mu \rightarrow \nu_\tau$. This channel requires a detector that can identify $\tau$ lepton. In that context the OPERA experiment [1] has been designed for the direct observation of $\nu_\tau$ appearance from $\nu_\mu \rightarrow \nu_\tau$ oscillation. The OPERA detector is located in Gran Sasso laboratory which is 730 km away from neutrino source at CERN. The CERN to Gran Sasso neutrino beam (CNGS) was designed and optimized for maximum oscillation probability and $\tau$ rate. A high intensity 400 GeV proton beam extracted from the SPS and directed to a graphite target. The positively charged $\pi$K are guided by two magnetic lenses; horn and reflector. In the 1000m long decay vacuum tube these particles mainly decay into muon and muon neutrino. All the remaining hadrons are stopped by a hadron dump located at the end of the decay tunnel. The dump is
followed by two muon detectors that provide information on the intensity and the profile of the beam. The resulting neutrino beam consists of muon-neutrinos at mean energy of 17 GeV and with a contamination of 2.1% of $\bar{\nu}_\mu$ and of 0.9% $\nu_e$. The prompt $\nu_\tau$ is negligible and therefore the beam is suitable for $\nu_\mu \rightarrow \nu_\tau$ transitions in appearance mode.

2. The Experimental Set-up

The OPERA detector, shown in the Figure 1, consists of two identical modules each instrumented with ECC target and electronic detectors. The main goal that has driven the detector design is to observe the $\tau$ lepton produced in the charged-current interaction of $\nu_\tau$ at rest. This requires a micrometer tracking resolution which is achieved with nuclear emulsion. On the other hand, the neutrino cross-section is too small one also needs a large mass. In order to provide large target mass, the emulsion films are interleaved with 1 mm thick lead plates. This structure is historically called Emulsion Cloud Chamber (ECC) and present many advantages like a massive target with coupled to very precise trackers, as well as a standalone detector to measure electromagnetic shower and momentum of charged particles. But ECC itself can not give time information. For real-time detection of neutrino interaction and to provide the information for the location of neutrino interaction. The combination of ECC and electronic detectors is called hybrid set-up.

The emulsion film production was done by Fuji Film company. The transverse size of the emulsion film is $10.2 \times 12.5 cm^2$. It is composed of a 45 $\mu$m of a sensitive layer on both surface of a 205 $\mu$m thick plastic base. The nuclear emulsion is continuously sensitive; it records all tracks from the production until the development. The full production process of a film takes about one month so that films integrates about 2,000 tracks/cm$^2$ from the cosmic ray flux. In order to reduce the amount of tracks accumulated, a new procedure called refreshing was applied to all emulsion films [2]. It consists of keeping the emulsion films at high relative humidity and high temperature (for example at 98% relative humidity and 27 degree celsius for 3 days). A reduction of 98% of the accumulated tracks can be achieved by this process.

An ECC detector, so called brick, is made of 56 lead plates 1 mm thick interleaved with nuclear emulsions. Each brick weights 8.3 kg and has a thickness of 7.5 cm corresponding to 10 radiation length. This unit is cloned 150,000 times to reach an overall mass of 1.25 kton. In order to produce this amount of brick in a year, a dedicated machine, called Brick Assembly Machine (BAM), was designed. It is fully automated machine located in Gran Sasso. Nuclear emulsion films are interleaved lead plates and piled up by an anthropomorphic robot. Bricks are then placed in the brick walls. Instrumented target which is constituted by 31 wall planes and each plane houses 3328 bricks. The OPERA bricks are moved in and out of their supporting trays in the wall by means of automatic system called Brick Manipulator System (BMS). There are two BMS machines on each side of the experiment. Each wall plane is followed by a double layer of plastic scintillators that provide real-time tracking of the outgoing charged particles. Each wall is made of a plane of four horizontal modules
followed by a plane of vertical ones thus providing 2D track information. A module consists of 64 scintillator strips wavelength shifting fibers and multi-mode PMT were used as read-out. In order to reduce the emulsion scanning load, the Changeable Sheets (CS) are attached to the downstream face of each brick and can be removed without opening the brick. The CS is used for a precise prediction of the position of the tracks in the most downstream film of the brick, hence guiding the vertex finding procedure. The scanning of emulsion films has been performed by fully automatic scanning systems. There are two types of scanning system, one is in Europe [3] and other in Japan [4]. They are differ both in hardware and software architecture. But they have similar performances.

Muon identification and charge measurement are needed for the study of the muonic $\tau$-decay channel and for the suppression of the background from the decay of charmed particles. Each muon spectrometer consists of a dipolar magnet made of two iron arms for a total weight 990 ton. The measured magnetic field intensity is 1.52 T. The two arms are interleaved with vertical 8m long drift-tube planes for the precise measurement of the muon track bending. The planes of Resistive Plate Chambers (RPC) are inserted between the iron plates of the arms, providing inside magnet, range measurement of the stopping particles. Finally, two glass RPC planes have been mounted in front of the first target (“VETO”) charged particles to help the rejection of charged particles originating outside the target fiducial region.

Figure 1: A view of the OPERA detector.
3. Data Analysis

The event analysis is initiated by the electronic detectors. The Target Tracker triggers the neutrino interaction and identifies the brick most probably containing the interaction. Then, the brick is removed from the target wall by BMS. The brick finding is one of the most critical operations for the success of the experiment. The brick efficiency has two components: the efficiency of brick-wall finding and efficiency of brick finding. The probability of identifying the correct wall has been evaluated to be about 95%. The brick finding efficiency is about 80%, based on the Monte Carlo simulation. After the extraction of the brick, X-ray spots are printed on CS doublet to have a reference frame. The CS doublet is detached from the brick and developed in the underground facility. For events with a muon in the final state, a prediction for the slope of the muon and its impact on the brick is also given with an accuracy at centimeter level. An area of $5 \times 5 \, \text{cm}^2$ on CS is scanned around the extrapolated position of the muon track. Both CSs are scanned independently for gathering high efficiency. If the track is found at least 3 out of 4 emulsion layers, it is visually inspected for the validation. If a track is found in CS doublet, the lateral X-ray marks are printed on the brick to speed up the scanning speed. In order to improve alignment accuracy, the brick is also exposed to cosmic rays at the surface. The exposure time is set to about 24 hours so that in total about 240 particles/cm$^2$ are available for precise alignment. All candidate tracks are searched for in the most downstream plate in the brick. The found tracks on the downstream film are then followed up until they disappear with a procedure called scan-back. This phase of the scanning is called event location. If the track is not found in three consecutive plates, the first of these is called vertex plate which may contain the neutrino interaction or the decay vertex or both. Once the vertex plate is identified a second phase of scanning has been performed in order to do a detailed analysis of the neutrino interaction. This scanning includes recording all micro-tracks in the fiducial volume of $1 \times 1 \times 1.3 \, \text{cm}^3$ around the stopping point.

The $\tau$ decay channels that will be investigated in the experiment are: $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$, $\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$ and $\tau^- \rightarrow h^- (n\pi^0) \nu_\tau$. Based on the decay length, they are classified in 2 categories as long and short decays. In the long decay topology, the $\tau$ does not decay in the lead plate where it is produced. The $\tau$ candidate is selected on the basis of the impact parameter of the $\tau$ and daughter tracks ($\theta_{kink} \geq 10 \, \text{mrad}$). In the short decay category the $\tau$ decays in the plate where it is produced. The short decays are selected on the basis of the impact of the daughter track with respect to the neutrino interaction vertex. This category is used only for the electron and muon channels. Table 1. summaries the experiment performance after 5 years of running. The number of expected signal events from $\nu_\mu \rightarrow \nu_\tau$ oscillations is given as a function of $\tau$ decay channel for three different values of $\Delta m^2$ at full mixing. The main background sources are charm decays, hadron interactions and large angle muon scattering.
Table 1: Summary of the expected numbers of $\tau$ in five years for different $\Delta m^2$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Rec. eff. $\times$ BR(%)</th>
<th>$\Delta m^2_{23}$</th>
<th>$\Delta m^2_{32}$</th>
<th>Bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \to \mu^-$</td>
<td>3.74</td>
<td>2.90</td>
<td>4.20</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \to e^-$</td>
<td>3.08</td>
<td>3.50</td>
<td>5.00</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \to h^-$</td>
<td>3.19</td>
<td>3.10</td>
<td>4.40</td>
<td>0.24</td>
</tr>
<tr>
<td>$\tau \to 3h^-$</td>
<td>1.05</td>
<td>0.90</td>
<td>1.30</td>
<td>0.17</td>
</tr>
<tr>
<td>Total</td>
<td>11.06</td>
<td>10.40</td>
<td>14.90</td>
<td>0.75</td>
</tr>
</tbody>
</table>

4. Conclusion

The first technical run was took place in August 2006 [5]. This was a low intensity run with a total integrated intensity of $7.6 \times 10^{17}$ p.o.t. 319 neutrino interactions were recorded in agreement with the expectation of 300 events. The reconstructed zenith-angle distribution from penetrating muon tracks is centered at 3.4 with a 10% statistical error in agreement with the expected value of 3.3. In October 2007, the first physics run was held 40% of target section filled bricks. The run was short due to failure of the ventilation control units of the proton target. In total 38 events were triggered in the OPERA detector corresponding to $0.82 \times 10^{18}$ p.o.t. This run allowed us to test the electronic detectors, data acquisition and brick finding algorithms. The 2008 run was finished in November with fully filled target. An integrated luminosity of $1.78 \times 10^{19}$ was accumulated. Corresponding to this statistics OPERA recorded about 10100 events correlated in time with the CNGS beam. Event selection is based on GPS timing systems and synchronization between the OPERA detector and CNGS. In total 1700 events were triggered in the OPERA detector. The collected neutrino interactions allowed to check the complete analysis chain.

REFERENCES