IL NUOVO CIMENTO Vol. 35 C, N. 6 Novembre-Dicembre 2012
DOI 10.1393/ncc/i2012-11349-7

Colloquia: LaThuile12

OPERA neutrino oscillation results

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ricevuto il 7 Settembre 2012

Summary. — The OPERA experiment was designed to perform the first detection of $\nu_\mu \to \nu_\tau$ neutrino oscillations in a direct appearance mode. We present the analysis results of the 2008–2009 statistics corresponding to 4.88×10^{19} p.o.t. In this sample, one ν_τ candidate event has been observed in the $\tau \to h$ channel. The statistical significance of this observation is estimated to be 95%.

PACS 14.60.Pq – Neutrino mass and mixing.
PACS 25.30.Pt – Neutrino-induced reactions.

1. – Introduction

Neutrino oscillations were first observed by the Super-Kamiokande experiment [1] in 1998. In recent years, several other experiments [2] using atmospheric, solar, reactor and accelerator neutrinos have confirmed the existence of neutrino oscillations and measured the mixing parameters. However, the direct observation of the appearance of ν_τ from an oscillated ν_μ is still missing. The observation of ν_τ appearance in an accelerator neutrino experiment will unambiguously prove that $\nu_\mu \to \nu_\tau$ is the dominant channel for the neutrino atmospheric sector. This is the main goal of the OPERA experiment [3]. In particular, the aim is to find the signal events coming from ν_τ charged-current interactions:

$$\nu_\tau N \to \tau^- X, \tag{1}$$

followed by one of the following decay topologies:

$$\begin{aligned} \tau^- &\to \mu^- \bar{\nu}_\mu \nu_\tau \\ &\to e^- \bar{\nu}_e \nu_\tau \\ &\to h^- (n\pi^0) \nu_\tau \\ &\to h^- h^- h^+ (n\pi^0) \nu_\tau . \end{aligned} \tag{2}$$

The oscillation parameters and very short decay length (87 μm) of the tau require i) a long baseline, ii) high-energy neutrino beam and iii) a massive detector with a high spatial resolution. OPERA is exposed to the long-baseline CNGS ν_μ beam, 732 km away from its neutrino source at CERN. The average neutrino energy is ~ 17 GeV well above the production threshold for the tau. The $\bar{\nu}_\mu$ contamination in terms of interactions is 2.1%, the ν_e and $\bar{\nu}_e$ contaminations are lower than 1% while the prompt ν_τ in the beam is negligible. The challenge of the OPERA experiment is to achieve the very high spatial accuracy required for the detection of the tau inside a large-mass active target. The technology chosen for this challenge are emulsion films interleaved with lead plates, historically called Emulsion Cloud Chamber (ECC). The submicrometer spatial resolution of the nuclear emulsion allows a precise three-dimensional reconstruction of the neutrino vertex as well as of the decay vertex associated short-lived particles, including the tau. The large target mass given by the lead plates allows to collect enough statistics.

2. – The detector

OPERA is a hybrid detector made of two identical Super Modules (SM) each consists of a target section, of a scintillator tracker detector (TT) and a spectrometer. The total mass is 1250 kTons. A target section is a succession of walls filled with elements called bricks, interleaved with planes of scintillator strips composing the Target Tracker (TT) that provide real time detection of the outgoing charged particles.

The target sections consist of about 150000 ECC bricks and each of them is made of 56 lead plates and 57 emulsion films for a total weight of 8.3 kg. An OPERA emulsion film has two layers each 44 μm on both sides of base. The total thickness is about 290 μm. The transverse size is $12.5 \times 10.0\,\mathrm{cm}^2$. A pair of nuclear emulsion films are used as interface between electronic detector and ECC brick. Tightly packed doublets of emulsion films are glued to the downstream face of each brick and can be removed without opening the brick.

The electronic detectors trigger the readout, identify and measure the trajectory of charged particles and locate the brick where the interaction occurred. The momentum of muons are measured by the spectrometers which consist of a dipolar magnet made of two iron arms. The trajectory of muons are traced back through the scintillator planes up to brick where the track originates. When no muons are observed, the scintillator signals produced by electrons or hadronic showers are used to predict the location of the brick that contains the primary neutrino interaction vertex. A detailed description of the OPERA detector is given in [4].

The scanning of the emulsion films is performed with two different types of automatic microscope, the European Scanning System (ESS) and Japanese S-UTS. The European scanning system makes use of commercial subsystems in a software based framework. The horizontal stage movable in XY coordinates with a CMOS camera mounted on the optical axis along which it can be moved to change the focal plane. The control workstation hosts a motion control unit that directs the stage to the area to be scanned and drives the camera along the Z-axis to produce optical tomographic image sequences. Then, the images are enhanced by means of a vision processing board in the control workstation. The reconstructed clusters in an emulsion layer is called micro-tracks. The linking of two matching micro-tracks produces the base-track. The system can work at a speed of $20\,\mathrm{cm}^2$/h/layer. The Japanese system has been developed in Nagoya and is based on highly customized components. The feature of this system is removal of the stop and go process of the stage in the data taking stage. The optical system is moved by a piezo-electric device. The dedicated board make the track recognition, building micro-tracks. The system can reach the speed of $72\,\mathrm{cm}^2$/h/layer.

3. – Event location and decay search

During years 2008–2009, OPERA has collected 31576 triggers corresponding to 5.13×10^{19} protons on target. Among these events 5255 events reconstructed as occurring inside the OPERA target.

The first step of event location is the extraction of the brick from the target wall. Then the CS is detached and its films are searched for compatible with the electronic data to verify the brick selection. In the case this search is unsuccessful, the brick is equipped with a fresh CS and inserted back into the target. All tracks measured in the CS are searched in the most downstream films of the brick and followed back until they are not found in three consecutive films. The stopping point is considered as the signature either for a primary of a secondary vertex. The vertex is then confirmed by scanning a volume with a transverse size of $1\,\text{cm}^2$ on at least 6 films downstream and 2 films upstream of the stopping plate is scanned around each stopping point. The data are processed by an offline program to reconstruct all tracks originating inside the volume. These tracks are input for a vertex reconstruction algorithm which is tuned to find also decay topologies.

The mean efficiency of event location is found to be $74 \pm 2\%$ and $48 \pm 4\%$ for ν_μ charged-current(CC) and neutral-current(NC) events, respectively. The expected number of located events in the 2008–2009 data sample is 2978 ± 75. But the result presented in this paper comes from the decay search analysis of 2738 events corresponding to 92% of the located sample.

When a secondary vertex is found the kinematical analysis of the whole event is done using the ECC brick data. The momentum of charged particles are determined by multiple coulomb scattering [5] measured in the ECC brick. The energy of γ-rays and electrons is estimated by a Neural Network algorithm that uses the combination of the number of track segments in the emulsion films and the shape of the electromagnetic shower, together with the multiple Coulomb scattering of the leading tracks.

4. – The candidate event

By applying decay search procedure, one ν_τ candidate was observed in the 2008–2009 data sample. The candidate event has 7 prongs at primary vertex out of which 4 are identified as originating from a hadron and 3 have a probability lower than 0.1% of being caused by a muon. The parent track exhibits a kink topology and the daughter track is identified as produced by a hadron through its interaction. Its impact parameter with respect to the primary is $55 \pm 4\,\mu$m, the impact parameter for other tracks is smaller than $7\,\mu$m. Two γ-rays point to the secondary vertex. The event passes all selection criteria described in [3] and summarized in table I. The invariant mass of two γ-rays is $120 \pm 20(\text{stat.}) \pm 35(\text{syst.})\,\text{MeV}/c$. If we assume the secondary hadron is π^- the invariant mass becomes $640^{+125}_{-80}(\text{stat.})^{+100}_{-90}(\text{syst.})\ \text{MeV}/c^2$ the decay mode is compatible therefore with being $\tau^- \to \rho^-(777)\nu_\tau$ whose branching ratio is about 25%. A detailed description of the candidate event can be found in [6].

5. – Background estimation

The charmed particles have lifetimes similar to that of the tau and have similar topologies. The finding efficiency of the decay vertices is therefore also similar to that of tau decays. Comparing the observed charm event sample with simulation would be a test for corresponding efficiencies and backgrounds. Table II shows the

TABLE I. – *Selection criteria for* ν_τ *candidate event.*

Varibale	Cut-off	Candidate Event
Missing P_T at Primary Vertex (GeV/c)	< 1.0	$0.57^{+0.32}_{-0.17}$
Angle between parent track and primary hadronic shower in the transverse plane	$\frac{\pi}{2}$	3.01 ± 0.03
Kink angle (mrad)	> 20	41 ± 2
Daughter momentum (GeV/c)	> 2	12^{+6}_{-3}
Daughter P_T when γ-ray at the decay vertex (GeV/c)	> 0.3	$0.47^{+0.24}_{-0.12}$
Decay length (μm)	< 2000	1335 ± 35

TABLE II. – *The observed and expected charm topologies in the* 2008–2009 *sample.*

Topology	Observed charm events	Expected charm events with background
C1	13	17.8
V2	18	16.5
C3	5	5.8
V4	3	2.1
Total	39	42.2 ± 8.3

comparison between observed charm events and expected from simulation. There is a good agreement between them.

The main background source to all τ decay channels is constituted by charmed particle production in ν_μCC interactions where the primary lepton is not identified. The charm background was evaluated using charm cross-sections measured by the CHORUS Collaboration [7].

TABLE III. – *Expected number of signal and background events in the* 2008–2009 *sample.*

Decay channel	Number of signal for 4.88×10^{19} p.o.t	Number of background for 4.88×10^{19} p.o.t
$\tau \to \mu$	0.39	0.02 ± 0.01
$\tau \to e$	0.63	0.05 ± 0.01
$\tau \to h$	0.49	0.05 ± 0.01
$\tau \to 3h$	0.15	0.04 ± 0.01
Total	1.65	0.16 ± 0.03

The second main source of background in $\tau \to h$ decay channel comes from one-prong inelastic interactions of primary hadrons produced in ν_μNC interactions or in ν_μCC interactions where the primary lepton is not identified and in which no nuclear fragments can be associated with secondary interaction. This background has been evaluated with Monte Carlo simulation based on FLUKA [8] and cross-checked with data.

6. – Conclusion

The OPERA experiment, aiming at the first detection of neutrino oscillations in direct appearance mode where the oscillated neutrino is identified. The analysis of the 2008–2009 data corresponding to 4.88×10^{19} p.o.t. intensity has been completed and a single ν_τ candidate event which is compatible with the expectation was observed. All background sources and expected number of tau events are summarized in table III. The significance of the observation of one decay in the $\tau \to h$ channel is found to be 95%. Considering all decay channels, the number of expected signal and background events are respectively 1.65 ± 0.41 and 0.16 ± 0.03(syst.), the probability for the event to be background being 15%.

The analysis of 2010–2011 data samples is in progress.

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This work is supported by TUBITAK under Grant No. 108T324.

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