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STATUS OF THE OPERA NEUTRINO OSCILLATION EXPERIMENT*

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The OPERA neutrino detector at the underground Gran Sasso Laboratory (LNGS) was designed to perform the first detection of neutrino oscillations in appearance mode through the study of $\nu_\mu \to \nu_\tau$ oscillations. The apparatus consists of a lead/emulsion-film target complemented by electronic detectors. It is placed in the high-energy, long-baseline CERN neutrino beam (CNGS) 730 km away from the neutrino source. Runs with CNGS neutrinos were successfully carried out in 2008–2009 with the detector fully operational with its related facilities for the emulsion handling and analysis.

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1. Introduction

Neutrino oscillations were anticipated nearly 50 years ago but they have been unambiguously observed only recently. Several experiments carried out in the last decades with atmospheric and accelerator neutrinos, as well as with solar and reactor neutrinos, contributed to our present understanding of neutrino mixing (see *e.g.* [1] for a review). As far as the atmospheric neutrino sector is concerned, accelerator experiments can probe the same oscillation parameter region as atmospheric neutrino experiments. This is the case of the OPERA experiment [2–4] that has the main scientific task of the first direct detection of $\nu_\mu \to \nu_\tau$ appearance, an important missing tile in the oscillation scenario.

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2. CNGS neutrino beam

OPERA uses the long-baseline ($L = 730\,\mathrm{km}$) CNGS neutrino beam [5] from CERN to LNGS, the largest underground physics laboratory in the world. The beam consists mainly of ν_μ with a mean energy of about 17 GeV, with a $\overline{\nu_\mu}$ contamination of 4% and $\nu_e + \overline{\nu_e}$ contamination of $\sim 0.9\%$. The high energy of the beam (above the threshold for τ lepton production) and the fact that the ν_τ prompt contamination is totally negligible make the beam suitable for the study of $\nu_\mu \to \nu_\tau$ transitions in appearance mode. The beam energy was optimized to maximize the τ rate at the detector site and results from a compromise between two opposite requirements: a significant charged-current (CC) interaction cross-section of the oscillated ν_τ which occurs at high energy values, and a large oscillation probability favoring low energies.

Assuming a CNGS beam intensity of 4.5×10^{19} p.o.t. per year and a five years run about 24 300 CC plus neutral current (NC) neutrino events will be collected by OPERA from interactions in the lead-emulsion target. Out of them 74 (167) CC ν_τ interactions are expected for oscillation parameter values $\Delta m^2_{23} = 2 \times 10^{-3}\,\mathrm{eV}^2$ $(3 \times 10^{-3}\,\mathrm{eV}^2)$ and $\sin^2 2\theta_{23} = 1$. Taking into account the overall τ detection efficiency the experiment should gather 10–15 signal events with a background of less than one event.

3. OPERA detector

The detection of τ lepton produced in the CC interaction of a ν_τ sets two conflicting requirements: a large target mass to collect enough statistics and an extremely high spatial accuracy to observe the short-lived τ lepton ($c\tau = 87.11\,\mu\mathrm{m}$).

The τ lepton is identified by the detection of its characteristic decay topologies either in one prong (electron, muon or hadron) or in three-prongs. Short track of τ lepton is measured with a large mass target made of lead plates (target mass and absorber material) interspaced with thin nuclear emulsion films (high-accuracy tracking devices). This detector is historically called Emulsion Cloud Chamber (ECC). Among past applications it was successfully used in the DONUT experiment for the first direct observation of the ν_τ [8].

The whole lead/emulsion target is segmented into modules (hereafter called ECC bricks) which can be selectively extracted, developed, and analyzed soon after the interaction has occurred. Each brick (see Fig. 1) consists of 56 lead plates of 1 mm thickness interleaved with 57 emulsion films [6]. The transverse dimensions of the brick are $12.8 \times 10.2\,\mathrm{cm}^2$ and the thickness along the beam direction is 7.9 cm (about 10 radiation lengths).

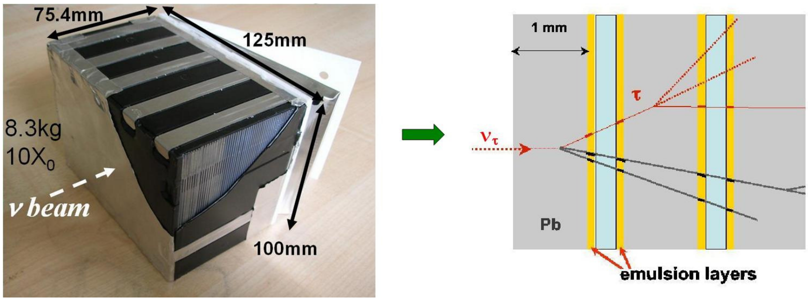

Fig. 1. ECC Brick: form (left) and scheme of the internal structure with one typical ν_τ detection topology (right).

The OPERA detector (see Fig. 2) is a hybrid detector made of two identical Super Modules (SM) each consisting of a target section of about 625 tons made of $\sim$ 75 000 ECC bricks, of a scintillator tracker detector (Target Tracker, TT) needed to trigger the read-out and localize neutrino interactions within the target, and of a muon spectrometer. The detector is equipped with an automatic machine (the Brick Manipulator System, BMS) that allows the removal of bricks from the detector. Ancillary, large facilities are used for the handling, the development and the scanning of the emulsion films.

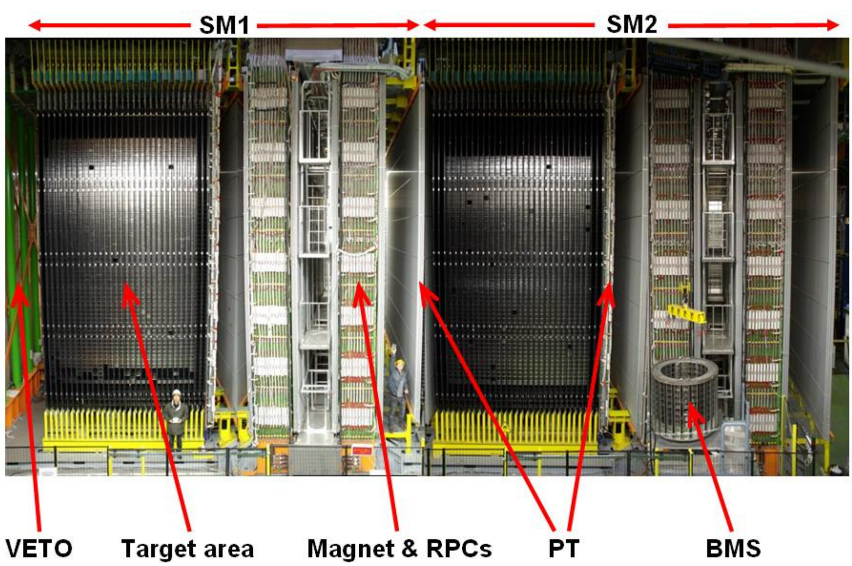

Fig. 2. View of the OPERA detector. The neutrino beam enters from the left. Arrows show the position of the VETO planes, the target and TT, the drift tubes (PT), the magnets and the resistive plates chambers (RPC) installed between the magnet iron slabs.

4. Vertex brick identification

An essential problem in OPERA is identification of the best candidate brick to contain a neutrino interaction vertex called brick finding (BF). No new bricks are inserted in the detector, so the total target mass is gradually decreasing with time. Therefore, a high efficiency of the BF allows to minimize the target mass loss and to reduce emulsion scanning load.

Identification of the brick containing the neutrino interaction vertex is carried out in the two following steps.

First, event reconstruction in electronic detectors is performed. It combines tracking information with the output of a Neural Network for the selection of the most probable wall where the interaction occurred, and provides a list of bricks with the associated probability that the interaction occurred therein. For events with a muon in the final state, a prediction for the slope of the muon and its impact on the brick is provided. For NC events a hadronic shower calculated with TT hits provides general direction to the vertex. An example of a 2009 neutrino event is shown in Fig. 3.

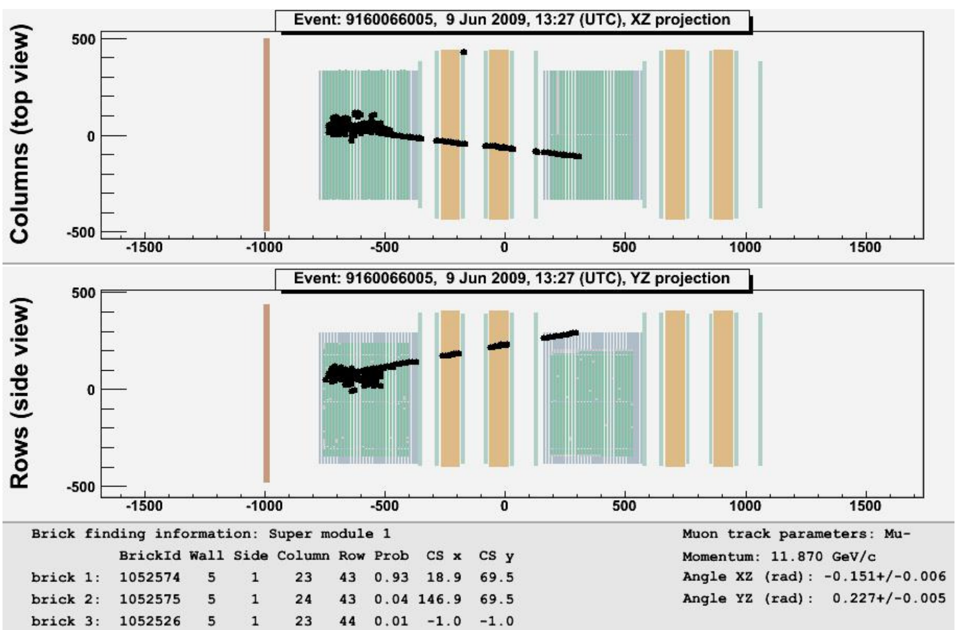

Fig. 3. Neutrino event as registered by the electronic detectors.

A preliminary estimate of the BF efficiency, limited to the extraction of the first most probable brick is compatible with the Monte Carlo estimate of 70% computed for a standard mixture of CC and NC events.

The second step includes analysis of two interface emulsion films called Changeable Sheets (CS) that are inserted in between each ECC brick and TT scintillator strips (see Fig. 4). The CS technique has already been successfully applied earlier to all past hybrid experiments like E531 [7], CHORUS [9], and DONUT. Before a brick is disassembled the CS doublet is analyzed in the scanning facilities in order to confirm the electronic predictions. The information of the CS is then used for a precise prediction of the position of the tracks in the most downstream films of the brick, hence guiding the scan-back vertex finding procedure. If no tracks are found in the CS, the brick is returned back to the detector with another CS doublet attached; otherwise, it is dismantled, developed and sent to one of scanning laboratories in Europe or in Japan.

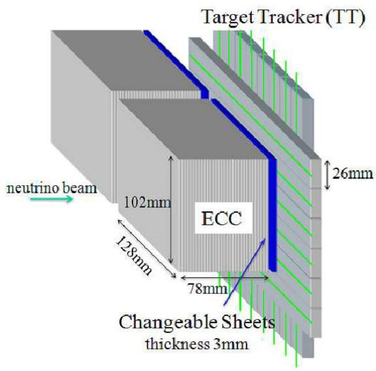

Fig. 4. Schematic view of the bricks with their CS attached in front of TT planes.

5. Analysis of emulsion

OPERA is the first very large scale emulsion experiment. Its 150 000 ECC bricks include about 110 000 m^2 emulsion films. The scanning of the events is performed with fully automated microscopes of two different types (see Fig. 5): the European Scanning System (ESS) and the Japanese Super-Ultra Track Selector (S-UTS). Each of them is faster by about two orders of magnitude than those used *e.g.* in the CHORUS experiment. Their routine scanning speed varies from 20 to 75 cm^2/h/layer, 24 hours/day. Both systems demonstrate $\sim 0.3\mu$ m spatial resolution, ~ 2 mrad angular resolution and $\sim 90\,\%$ base track detection efficiency.

CS scanning is performed in the area around the electronic detector predictions: $\sim 25\,\mathrm{cm}^2$ for CC events and $\sim 70\,\mathrm{cm}^2$ for NC events. The scanning is done independently on both CS, in order to maximize track detection efficiency. Resolution of the electronic detector predictions is ~ 9 mm for track position and ~ 20 mrad for track slope.

Fig. 5. The European (left) and Japanese (right) scanning systems.

All tracks measured in the CS are sought in the most downstream films of the brick and followed back until they are not found in three consecutive films (scan-back procedure). The stopping point is considered as the signature either for a primary or a secondary vertex. The vertex is then confirmed by scanning a volume with a transverse size of 1 cm^2 for 11 films in total, upstream and downstream of the stopping point.

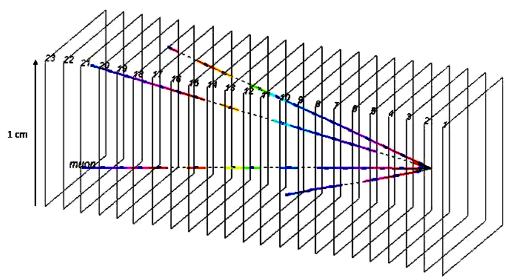

Fig. 6. Example of located neutrino interaction vertex.

The tracks attached to the primary vertex are followed downstream, with a procedure analogous to scan-back but in the opposite direction, to check whether they show any decay topology and measure their momentum.

6. Decay topologies

Charm production and decay topology events have a great importance in OPERA for two main reasons. On one hand in order to certify the observation of τ events one should prove the ability of observing charm events at the expected rate. On the other hand, since charm events exhibit similar topology as τ decays, they are a potential source of background if the muon at the primary vertex is not identified. Therefore, searching for charm-decays in events with the primary muon correctly identified provides a direct measurement of this background.

7. Progress of the experiment

First neutrino data were collected by OPERA in 2006 [3] with the electronic detectors alone and then in 2007, 2008, and 2009 with target bricks installed. Unfortunately, due to a fault of the CNGS facility, the 2007 physics run lasted only a few days and brought very few events. The beam intensity collected up to now is $\sim 5.3 \times 10^{19}$ p.o.t. About 5400 on-time neutrino events registered in the target. Analysis of 2008 run has been finished. Analysis of 2009 run is in progress.

Charm decay topologies were searched for in the sample of $\sim$ 1000 located CC neutrino interactions. Twenty six events with charm-like topologies were found which is in agreement with the neutrino-induced charm-production cross-section measured by the CHORUS experiment [10].

8. Conclusion and outlook

The 2008–2009 CNGS runs constitute an important milestone for the LNGS OPERA experiment searching for $\nu_\mu \to \nu_\tau$ oscillations. Initial samples of neutrino interaction events have been collected in the emulsion/lead target and allowed to check the complete analysis chain starting from the trigger down to the neutrino vertex location in the emulsions and to the topological and kinematical characterization of the event.

The overall performance of the experiment during the running phase and through the analysis chain can be summarized by stating that:

- all electronic detectors performed excellently allowing the precise localization of the brick hit by the neutrino;
- the electronic detector event reconstruction was tuned to the brick finding procedure which operated with real neutrino events providing good results;
- all experimental activities from brick removal upon identification to the emulsion analysis, have been successfully accomplished;
- the scanning of the Changeable Sheets can be performed with the expected detection efficiencies;
- vertex location was successfully attempted for both CC and NC events. $\sim$ 1400 vertices have been located in ECC up to now;
- the topological and kinematical analysis of the vertices were successfully exploited and led to an unambiguous interpretation of neutrino interactions. About 30 events with a charm-like topology were found so far in the analyzed sample. This is fully consistent with expectations based on the known neutrino-induced charm production cross-section.

OPERA continues to accomplish its task of selecting decay topologies in the emulsions from a large number of interactions triggered by the electronic detectors and that the scene has been set for the discovery of ν_τ appearance.

Detailed studies currently in progress with simulated events and real data will allow to assess the experimental efficiencies, backgrounds and sensitivity.

Coming 2010 run is expected to be a nominal one with the beam intensity of $\sim 4.5 \times 10^{19}$ p.o.t.

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