ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2011. Т. 42. ВЫП. 4

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The OPERA experiment at the underground Gran Sasso Laboratory (LNGS) has to perform the first detection of neutrino oscillations in appearance mode through the direct observation of $\nu_\mu \to \nu_\tau$. 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 first candidate event $\nu_\mu \to \nu_\tau$ recently detected.

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INTRODUCTION

A possibility of neutrino oscillations was proposed nearly 50 years ago but their existence was finally proved in 1998 [1]. Several experiments carried out in the last decades with atmospheric, solar neutrinos, accelerator and reactor neutrinos, contributed to a current understanding of neutrino mixing (see, e.g., [2] for a review). As far as the atmospheric neutrino sector is concerned, accelerator experiments can probe the same oscillation parameter region but with a much better control of neutrino parameters. The main goal of the OPERA experiment [3, 4] is a first direct detection of $\nu_\mu \to \nu_\tau$ oscillations through an observation of appearance of the ν_τ in a primarily pure ν_μ beam. Although such an oscillation mechanism is the most popular explanation of the atmospheric neutrinos anomaly and deficits of ν_μ in the accelerator neutrinos experiments [5, 6], its direct and unambiguous detection is still an important missing tile in the oscillation scenario.

1. NEUTRINO BEAM AND OPERA DETECTOR

OPERA uses the long-baseline ($L = 730$ km) CNGS neutrino beam [7] from CERN to LNGS, the largest underground physics laboratory in the world. The beam consists mainly of ν_μ with a $\overline{\nu_\mu}$ fraction of 4% and $\nu_e + \overline{\nu_e}$ contamination of $\sim 0.9\%$. The high energy of the beam (a mean value of about 17 GeV) 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 favouring low energies.

Assuming a CNGS beam intensity of $4.5 \cdot 10^{19}$ p.o.t. (protons on target) per year and five years of the detector operation, about 24000 CC and neutral-current (NC) neutrino events will be collected by OPERA from interactions in the lead/emulsion target. Taking into account the present value of the oscillation parameters and the overall τ detection efficiency, the experiment should gather about 10 signal events with a background of less than one event.

The detection of τ leptons 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 (a typical pathlength is a few hundreds micrometers at the CNGS energy). A solution for this problem is in the use of the so-called Emulsion Cloud Chamber (ECC): a stack of thin lead plates (target mass and absorber material) interspaced with nuclear emulsion films (high-accuracy tracking devices). Such a structure has a capability to detect a short track of τ lepton as well as products of its characteristic decay modes. It was proved by the DONUT experiment where tau neutrinos were observed for the first time by the same ECC detection technique [8]. OPERA (see Fig. 1) is a hybrid detector, it includes electronic detectors for triggering on

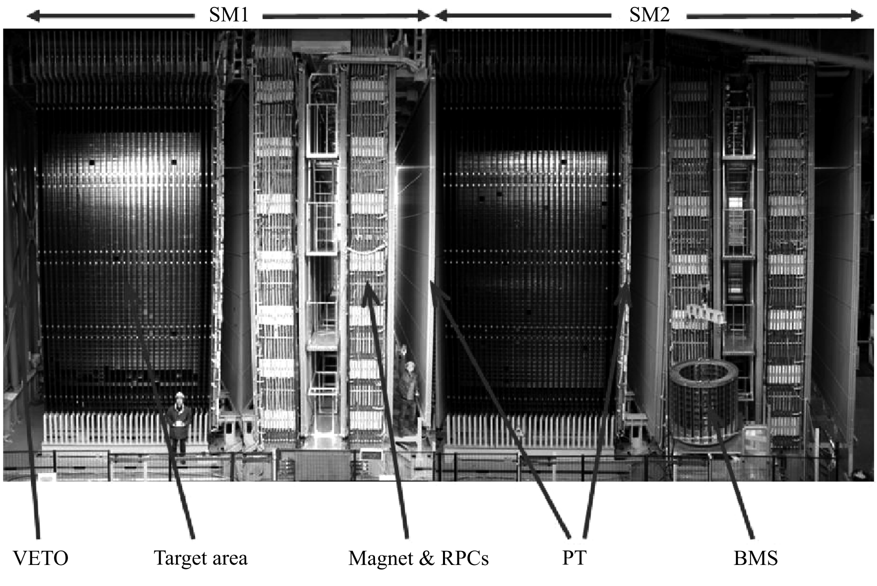

Fig. 1. View of the OPERA detector. The neutrino beam enters from the left. Arrows show the position of the VETO planes, the target and TT, the drift tubes (PT), the magnets and the resistive plates chambers (RPC) installed between the magnet iron slabs

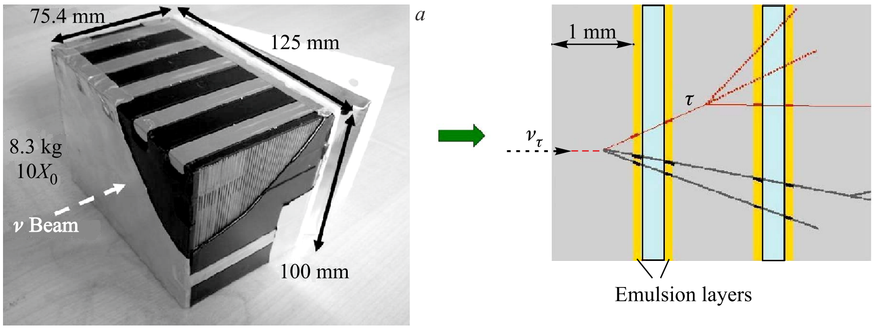

Fig. 2. ECC brick: form (a) and scheme of the internal structure with one typical ν_τ detection topology (b)

neutrino events, location of the vertexes and muon momentum measurement, and nuclear emulsions to detect τ leptons and their decay products. The detector is made of two identical Super Modules (SM) each consisting of a target section of about 625 t, 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 whole lead/emulsion target is segmented into blocks (hereafter called ECC bricks) which can be selectively extracted, developed, and analyzed soon after the interaction has occurred. Each brick (see Fig. 2) consists of 56 lead plates of 1 mm thickness interleaved with 57 emulsion films. The transverse dimensions of the brick are 12.8×10.2 cm and the thickness along the beam direction is 7.9 cm (about 10 radiation lengths). 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. The OPERA detector is described in detail in [9].

2. VERTEX BRICK IDENTIFICATION

Neutrino events analysis starts with processing of signals from the electronic detectors, reconstructing tracks of particles outgoing from the vertex, and measuring muons momentum in the magnetic spectrometer. Tracking information is combined with reconstructed hadronic shower axis and the output of a Neural Network for the selection of the wall where the interaction occurred, providing 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. This part of the event analysis is called Brick Finding (BF). The brick with the highest probability is extracted from the detector for analysis. No new bricks are inserted in the detector during the experiment, so the total target mass is gradually decreasing with time. Therefore, a high efficiency of the BF is important for minimization of the target mass loss and the reduction emulsion processing load.

After extraction of the brick predicted in the electronic detectors, its validation is performed by analysis of two interface emulsion films (called Changeable Sheets, CS) [10] that are inserted in between each ECC brick and TT scintillator strips. The CS doublet is analyzed in the scanning facilities before a brick is disassembled. The information on 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 the scanning laboratories in Europe or in Japan.

3. ANALYSIS OF EMULSION

OPERA is the first very large scale emulsion experiment. Its 150000 ECC bricks include about 110,000 m^2 of emulsion films. An emulsion experiment of that scale became possible due to development of emulsion mass production technology [11] and enormous progress in scanning technique during last years. The scanning of the events is performed with fully automated microscopes of two different types: the European Scanning System (ESS) [12] and the Japanese Super-Ultra Track Selector (S-UTS) [13]. Their routine scanning speed varies from 20 to 75 cm^2/h/layer, 24 h/day. Both systems demonstrate ~ 0.3 μm spatial resolution, $\sim$ 2 mrad angular resolution and $\sim$ 90% base track detection efficiency. The emulsions processing starts with the CS scanning which is performed in the area around the electronic detector predictions: $\sim$ 25 cm^2 for CC events and $\sim$ 70 cm^2 for NC events. Resolution of the electronic detector predictions is $\sim$ 9 mm for track position and $\sim$ 20 mrad for track slope. 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 5 films upstream and 10 downstream of the stopping point. The present overall location efficiency averaged over NC and CC events, from the electronic detector predictions down to the vertex confirmation, is about 60%. A further phase of analysis is applied to located vertices, called decay search procedure, to detect possible decay or interaction topologies on tracks attached to the primary vertex. It is also searched for extra tracks from neutral decays, interactions and γ-ray conversions. When secondary vertices are found in the event, a kinematical analysis is performed, using particle angles and momenta measured in the emulsion films. For charged particles up to about 6 GeV/c, momenta can be determined using the angular deviations produced by Multiple Coulomb Scattering (MCS) of tracks in the lead plates [14] with a resolution better than 22% for charged particles passing through an entire brick at normal incidence. Momenta of muons reaching the spectrometer are measured with a resolution of 20% up to 30 GeV/c and the sign of their charge is determined [9]. The γ-ray search is performed in the whole scanned volume by checking all tracks having an impact parameter (IP) with respect to the primary or secondary vertices lower than 800 μm. The angular acceptance is $\pm$500 mrad. The γ-ray energy is estimated by a Neural Network algorithm that uses the combination of the number of segments and the shape of the electromagnetic shower and also the multiple Coulomb scattering of the leading tracks. The same method is applicable to electrons from ν_e CC interactions. The precision in the γ-ray attachment to a vertex depends on the conversion point inside the 1 mm thick lead plate. The typical resolution for γ-ray angle determination is 5 (3) mrad at 1 (3) GeV. The detection of decay topologies is triggered by the observation of a track with a large impact parameter with respect to the primary vertex. The IP of primary tracks is smaller than 12 μm after excluding tracks produced by very soft particles.

The results presented here come from the decay search analysis of about 35% of the 2008 and 2009 data sample, or, rescaled to the beam integrated intensity, to $1.89 \cdot 10^{19}$ p.o.t. Charmed particles have similar lifetimes as τ leptons and, if charged, share the same decay topologies. Being produced in ν_μ CC interactions, the location of their primary vertex is easier than that of muonless ν_τ CC interactions, where the τ lepton decays into hadrons or into an electron. Still, the primary vertex being located, the finding efficiency of the decay vertices is similar for both types of particles, although the selection criteria are more stringent in the case of the τ analysis that is aiming at minimal background. In the sample of ν_μ CC interactions that have been searched for, a total of 20 charm decays have been observed that survived selection cut-offs, in agreement with the number expected from a MC simulation, 16.0 ± 2.9. This demonstrates that the efficiency of the search for short-lived decay topologies is understood.

4. CANDIDATE EVENT TOPOLOGY AND TRACK KINEMATICS

The decay search procedure applied to the part analyzed so far of 2008–2009 data sample yielded one ν_τ candidate event with measured characteristics fulfilling the selection criteria a priori defined in the experiment proposal [3] and

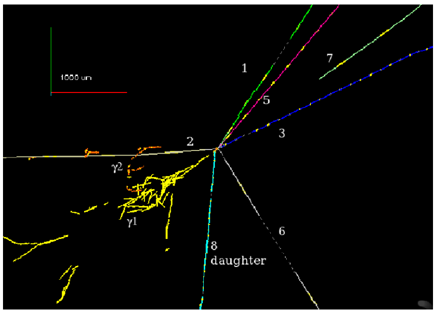

Fig. 3. Candidate event front view

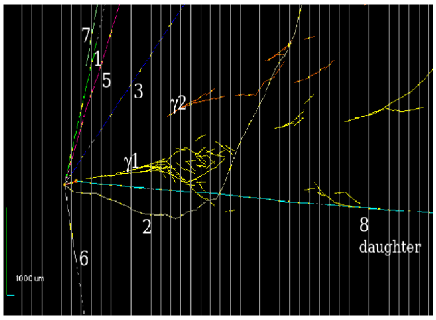

Fig. 4. Candidate event side view

its addendum [4]. Figures 3 and 4 show a front and side view of the event. For decays of the τ to a single charged hadron, it is required at the secondary vertex that:

— The kink angle $\theta_{\rm kink}$ is larger than 20 mrad.

— The secondary vertex is within the two lead plates downstream of the primary vertex.

— The momentum of the charged secondary particles is larger than 2 GeV/c.

— The total transverse momentum (P_T) of the decay products is larger than 0.6 GeV/c if there are no photons emitted at the decay vertex, and 0.3 GeV/c otherwise.

At the primary vertex, the selection criteria are:

— There are no tracks identified as a muon or an electron.

— The missing transverse momentum ($P_T^{\rm miss}$) is smaller than 1 GeV/c.

— The angle Φ in the transverse plane between the τ candidate track and the hadronic shower direction is larger than $\pi/2$.

A comprehensive study of the event performed independently with the European and Japanese scanning systems demonstrate consistent results:

• The primary neutrino interaction consists of 7 tracks of which one exhibits a visible kink.

• Two electromagnetic showers caused by γ rays are located in the event.

• Track 1 is left by a particle of momentum $0.78^{+0.13}_{-0.10}$ GeV/c most likely interacting in the target tracker following the wall where the interaction occured.

• Track 2 is left by a heavily ionizing particle. From its residual range and the value of pβ, the particle was identified as a proton with a momentum of (0.60 ± 0.05) GeV/c resulting from the residual range.

• Track 3 is left by a particle which generates a two-prong interaction 4 bricks downstream of the primary vertex. Its momentum is $(1.97 \pm 0.33 \pm 0.25)$ GeV/c.

• Track 4 exhibits a kink topology with an angle of (41 ± 2) mrad after a path length of (1335 ± 35) μm corresponding to 15$c\tau$ would it be that of a τ lepton. The expected γ factor from the kink angle is approximately 25. It is the parent track of a secondary interaction or decay. Both the kink angle and the path length satisfy the selection criteria.

• Track 5 has been followed in wall 12 and disappears in wall 13 after a total distance shorter than 174 g/cm^2. The particle has a momentum of $(1.30 \pm 0.22 \pm 0.16)$ GeV/c.

• Track 6 belongs to a pion of very low momentum $(0.36\pm0.18\pm0.09)$ GeV/c.

• Track 7 is not directly attached to the primary vertex and points to it with an IP $= 43^{+45}_{-43}$ μm. Its starting point is separated from this vertex by 2 lead plates. Its origin is likely to be a prompt neutral particle.

• Track 8, the kink daughter track, is left by a particle of a high momentum of 12^{+6}_{-3} GeV/c well above the 2 GeV/c selection cut-off and which generates a 2-prong interaction 7 walls downstream from its emission vertex. Its IP with respect to the primary vertex is (55 ± 4) μm. All the tracks directly attached to the primary vertex match the vertex point within 7 μm.

The total transverse momentum P_T of the daughter particles with respect to the parent track is $0.47^{+0.24}_{-0.12}$ GeV/c, above the lower selection cut-off at 0.3 GeV/c. Two gammas were associated with the secondary vertex. γ ray 1 has an energy of $(5.6 \pm 1.0\,(\mathrm{stat.}) \pm 1.7\,(\mathrm{syst.}))$ GeV; and γ ray 2, of $(1.2 \pm 0.4\,(\mathrm{stat.}) \pm 0.4\,(\mathrm{syst.}))$ GeV. The missing transverse momentum P_T^{miss} at the primary vertex is $0.57^{+0.32}_{-0.17}$ GeV/c. The invariant mass of γ rays 1 and 2 is $(120\pm20\,(\mathrm{stat.})\pm35\,(\mathrm{syst.}))$ MeV/c^2, supporting the hypothesis that they originate from a π^0 decay. Similarly, the invariant mass of the charged decay product assumed to be a π and of the two γ rays is $(640^{+125}_{-80}\,(\mathrm{stat.})^{+100}_{-90}\,(\mathrm{syst.}))$ MeV/c^2, which is compatible with the $\rho(770)$ mass. The more detailed kinematic analysis can be found in [15].

4.1. Background Estimation. The secondary vertex is compatible with the decay of a τ into $\mathrm{h}^-(n\pi^0)$. The two main sources of background to this channel, where a similar final state may be produced, are:

— the decays to a single charged hadron of charged charmed particles produced in ν_μ CC interactions where the primary muon is not identified as well as the $c\bar{c}$ pair production in ν_μ NC interactions when one charm particle is not identified and the other decays to a one-prong hadron channel;

— the one-prong inelastic interactions of primary hadrons produced in ν_μ CC interactions where the primary muon is not identified or in ν_μ NC interactions and in which no nuclear fragment can be associated with the secondary interaction.

The charm background produced in ν_μ interactions in the analyzed sample is estimated as $(0.007 \pm 0.004\,(\mathrm{syst.}))$ events. The dominant background from hadron re-interactions has been evaluated with a FLUKA [16] based Monte Carlo code. The probability for a background interaction to occur over 2 mm of lead and to satisfy the selection criteria for the reconstruction of the kink decay topology is $(3.8 \pm 0.2) \cdot 10^{-5}$ per NC event taking into account the cuts on the event global kinematics. This leads to a total of $(0.011 \pm 0.006\,(\mathrm{syst.}))$ background events when misclassified CC events are included. The total background in the decay channel to a single charged hadron is therefore $(0.018 \pm 0.007\,(\mathrm{syst.}))$. The probability that this background fluctuates to one event is 1.8% (2.36σ). If one considers all decay modes included in the search, the significance of the observation becomes 2.01σ.

CONCLUSION

The description and status of the OPERA experiment is presented. The first candidate ν_τ CC interaction in the OPERA detector at LNGS is detected after analysis of a sample of events corresponding to $1.89 \cdot 10^{19}$ p.o.t. in the CERN CNGS ν_μ beam. The expected number of ν_τ events in the analyzed sample is $(0.54 \pm 0.13\,(\mathrm{syst.}))$. The candidate event passes all the selection criteria, it is assumed to be a τ-lepton decay into $h^-(n\pi^0)\nu_\tau$. The observation of one possible tau candidate in the decay channel $h^-(\pi^0)\nu_\tau$ has a significance of 2.36σ of not being a background fluctuation. The data analysis of the 2009–2010 run is in progress, a few more candidates are required to firmly establish neutrino oscillations in direct appearance mode through the identification of the final charged lepton.

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