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The OPERA experiment: $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ physics program

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Abstract. An update the physics potential of the OPERA experiment is given for the $\nu_\mu \to \nu_\tau$ design goal as well as for the improved limit that can be reached on the unknown θ_{13} mixing angle by means of $\nu_\mu \to \nu_e$ search.

PACS. 14.60.Lm Ordinary neutrinos (nue, numu, nutau) – 14.60.Pq Neutrino mass and mixing

1 Introduction

The OPERA experiment [1], currently in construction in Hall C of the Gran Sasso laboratory, aims to conclusively reveal in the appearance mode the oscillation of ν_μ into ν_τ (see Sect. 4.1) using the dedicated high energy neutrino beam from CERN to Gran Sasso (CNGS). Besides this main stream of analysis, an extension of the search for θ_{13} mixing angle beyond the CHOOZ limit [2] can be achieved by OPERA, as described in Sect. 4.2.

2 The CNGS beam line

The ν_μ CNGS beam [3] between CERN and the Gran Sasso laboratory (730 km) will enter in operation in May 2006. It has been optimized for ν_τ appearance oscillations with a mean neutrino energy of 17 GeV. During one year, in a mode where the use of the SPS is shared with LHC and fixed target operations, it is expected that 4.5×10^{19} protons on target (pot) can be delivered, assuming 200 days of operation. Possible improvements to the proton beam line [4] would increase the proton intensity to 6.7×10^{19} pot. If not otherwise stated, this value will be used in this document. In the 1.8 ktons OPERA detector, the corresponding ν_μ flux will lead to about 46 events per day (see Table 1) with a contamination of 2.1% $\overline{\nu}_\mu$, 0.8% ν_e and less than 0.05% of $\overline{\nu}_e$. The ν_e contamination is a limiting factor for θ_{13} search. If the $\nu_\mu \to \nu_\tau$ oscillation hypothesis is confirmed, the number of τ's produced via charged current interactions at the Gran Sasso is about 20/kton/year for $\Delta m^2 = 2.5 \times 10^{-3}\mathrm{eV}^2$ at full mixing.

Table 1. ν_μ events in the 1.8 ktons OPERA detector per day with improved proton beam

Event type	number
NC	10.96
CC (DIS)	31.42
CC (QE + RES)	4.07
Total	46.45

3 The OPERA experiment

The main purpose that has driven the detector design is to observe the trajectories of the τ and of its decay products in thin layers of emulsion. To provide the large target mass (1.8 ktons) the emulsion films are interleaved with 1 mm thick low radioactive lead plates strengthened by small amount of calcium. An emulsion film in OPERA consists of two emulsion layers (50 μm thick) put on either side of a plastic base (200 μm thick). Before being assembled into bricks, all the films, produced by the Fuji company, will be refreshed to erase preexisting tracks occurred during the production and the storage phases. The basic structure, hereafter called a brick, is based on the Emulsion Cloud Chamber (ECC) concept. The efficiency of the ECC to detect τ decays had been already proved by the DONUT experiment [5].

3.1 The detector structure

The OPERA detector consists of 2 identical "super modules" (SM). Each SM has a target section and a muon spectrometer. The spectrometers measure the charge and the momentum of crossing muons by means of a dipolar magnet providing a 1.6 T magnetic flux density transverse to the neutrino beam axis, equipped with drift tubes for precise measurements and RPC chambers for pattern recognition. The targets are in total composed of 206336 bricks that will be installed by an automatic manipulator system into 62 walls containing 64 rows of 52 bricks and separated from each other by modules of electronic trackers.

A brick is obtained by stacking 56 lead plates (1 mm thick) and Fuji emulsion films, plus an extra emulsion film before, and another one, called Changeable Sheet (CS), behind after 2 mm of plastic. The CS can be detached from the rest of the brick for analysis, before proceeding to the development of the whole set of emulsions. In terms of radiation length, a brick corresponds to a thickness of 10 X_o.

Each electronic tracker module composed of 2 planes of 6.6 m long scintillator strips in the two transverse directions (X and Y) is installed downstream each brick wall. The main goal of this detector is to provide a trigger (99% efficiency) for the neutrino interactions and to identify the brick where the event has occurred. The strips, 2.6 cm wide and 1 cm thick, have WLS fibers for readout by 64 channels multi-anode Hamamatsu photomultiplier tubes with a dedicated electronics [6]. The efficiency to find the right brick is about 70–80% depending of the event type.

The candidate bricks will be daily removed by the manipulator system for subsequent analysis. It takes about 3 hours to change 50 bricks. The analysis of the emulsion films are performed using automatic scanning. The demonstration of the automatic scanning efficiency has no more to be proved. It has been pioneered by the Nagoya group and, in the recent years, applied in several european groups with somewhat different hardware and software configurations. The present routine scanning speed is around $1-5$ cm^2/hr depending on the scanning conditions and hardware. A speed of $20-40$ cm^2/hr will be reached with new systems presently under test at Nagoya and in european laboratories.

3.2 The detector performances

The leading muon detection is of prime importance for charm background rejection (it represents about 50% of the remaining background). For this purpose we exploit the electronic target tracker and the spectrometer to perform a first π/μ separation by an energy/range algorithm, then a matching criterium based on angular information is used to link the muon candidate recorded by the electronic detectors to the charged tracks reconstructed in the emulsion of the brick. This procedure leads to a muon identification efficiency higher than 95% while the probability to select a fake muon in a neutral current interaction is less than 10%. The charge of the muon can be determined with a (0.1-0.3)% misdetermination using the precision tracker. Note that further improvements to reduce the charm background is foreseen by measuring the ionisation in emulsion to distinguish π from μ for low energy tracks stopping in the target section.

The angular resolution for reconstructing a track in a film is about 2 mrad with a pointing accuracy of 0.3 μm. This is entirely limited by the scanning accuracy of the microscope present stage and the digitization. Using Multiple Coulomb scattering occurring in lead plates and precise angular measurements in films, it has been shown with test beams that a resolution better than 20% for momentum below 4 GeV can be achieved using only half a brick (5 X_o).

The high precision in reconstructing track segments in films also makes the brick a good electromagnetic calorimeter. The efficiency to identify such showers is about 90%. A 5% π/e misidentification under high density track condition has been measured on test beam. Monte Carlo analysis have shown that under the extreme low track density in OPERA running conditions, this π/e misidentification would reduce to a few per mill.

The shower energy can be measured by counting the number of track segments reconstructed in a cone of 50 mrad around the incoming electron direction. This technique gives an energy resolution of $40\%/\sqrt{E}$ measured in test beam.

4 Physics performances

4.1 $\nu_\mu \to \nu_\tau$ search

The channels investigated by OPERA are the τ decays into electron, μ or a single charged hadron. They are classified in 2 categories, long and short decays, depending on the location of the tau decay vertex. In the long decay category the τ does not decay in the lead plate where it is produced and its track can be entirely reconstructed in one film. The τ candidate events are selected on the basis of the existence of a kink angle between the τ and the daughter tracks ($\theta_{kink} > 20$ mrad). In the short decay category the τ decays in the lead plate where it is produced. These events are selected on the basis of the impact parameter of the τ daughter track with respect to the interaction vertex (IP $>$ 5-20 μm). This category is used only for the electron and muon channels.

Table 2 summarizes the OPERA performance after 5 years of running. The number of expected signal events from $\nu_\mu \to \nu_\tau$ oscillations is given as a function of the studied channel for three different values of Δm^2 at full mixing. The total efficiency including the branching ratios amounts to 9.1% and the total background is estimated to be less than 1.06 event. The main background sources are

Table 2. Summary of the expected numbers of τ events in 5 years for different Δm^2 compatible with the Super Kamiokande results [7], with the expected background per decay channel. The numbers have been computed using the nominal design flux (numbers in parenthesis) and a flux increased by 50% corresponding to 3.38×10^{20} pot

channel	signal for Δm^2 (10^{-3}eV^2)			Bkg
	1.3	2.0	3.0	
$\tau \to$e	1.8 (1.2)	4.1 (2.7)	9.2 (6.1)	0.31 (0.21)
$\tau \to \mu$	1.4 (0.9)	3.4 (2.3)	7.6 (5.1)	0.33 (0.22)
$\tau \to$h	1.5 (1.0)	3.5 (2.3)	7.8 (5.2)	0.42 (0.28)
Total	4.7 (3.1)	11.0 (7.3)	24.6 (16.4)	1.06 (0.71)

charm decays (54%), hadron interactions (30%) and large angle muon scattering (16%). The probability to get at least 4σ significance after 5 years for $\Delta m^2 > 1.3\times10^{-3}\mathrm{eV}^2$ is 45% and reach 95% for $\Delta m^2 > 2.0 \times 10^{-3}\mathrm{eV}^2$. Using the atmospheric result to constrain the mixing angle the precision on Δm^2 at 2.5×10^{-3} eV^2 is about 16%.

4.2 $\nu_\mu \to \nu_e$ search

In addition to the dominant $\nu_\mu \to \nu_\tau$ oscillation, subleading transition involving ν_e might occur as well in a 3 flavours general framework. For instance, assuming a one-mass dominant spectrum ($\Delta m^2_{12} << \Delta m^2_{23} = \Delta m^2_{13} = \Delta m^2$), oscillation probabilities can be expressed like:

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(1.27\Delta m^2 L/E)$$
$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2 L/E)$$

The $\nu_\mu \to \nu_e$ oscillation at the atmospheric scale (Δm^2) is driven by the mixing angle θ_{13} which is constrained by CHOOZ experiment to be small ($\theta_{13} < 11^o$ for $\Delta m^2 = 2.510^{-3}\mathrm{eV}^2$) [2]. The analysis principle is based on a search for an excess of ν_e CC events at low neutrino energies [8]. The main background comes from the 1% electron neutrino contamination present in the beam. The analysis also takes into account the ν_τ events with a τ decaying into an electron since both oscillations would occur.

The sensitivity to θ_{13} is obtained by exploiting the kinematical differences between signal and background samples. For each hypothesis on the oscillation parameters, a χ^2 minimization is performed on the simulated distributions of visible energy, missing transverse momentum and electron transverse momentum. Table 3 summarizes the expected number of signal and background events in three family mixing and using the expected ν_e beam contamination. The limit obtained at 90% CL on θ_{13} is 7.1^o after 5 years running at nominal design flux. With an improved beam, the limit would reach 6.4^o. It yields that a limit can be reached which leads to significant improvement over the actual CHOOZ limit and open a window on the third mixing angle even in a neutrino beam optimized for ν_τ appearance mode.

Table 3. Expected number of signal and background events in 5 years obtained in the search of $\nu_\mu \to \nu_e$ for 3 values of θ_{13} and $\Delta m^2_{23} = 2.510^{-3}\mathrm{eV}^2$ and $\theta_{23} = 45^o$. The flux hypothesis are the same as for Table 2

θ_{13} (deg)	signal $\nu_\mu \to \nu_e$	ν_eCC	$\nu_\mu \to \nu_\tau$ $\tau \to$e	ν_μ NC	ν_μ CC
9	13.9 (9.3)	27 (18)	6.7 (4.5)	7.8 (5.2)	1.5 (1.0)
7	8.7 (5.8)	27 (18)	6.9 (4.6)	7.8 (5.2)	1.5 (1.0)
5	1.8 (1.2)	27 (18)	7.0 (4.7)	7.8 (5.2)	1.5 (1.0)

5 Conclusion

The ν_τ appearance is still an important missing piece of the neutrino oscillation puzzle for the atmospheric sector. The OPERA detector is designed to study this subject and its performances has been estimated with the foreseen CNGS flux. Even not optimized for that purpose, the CNGS beam has potentially an opportunity to improve the present limit on the θ_{13} mixing angle. In the future, OPERA detector might be a valuable concept in the framework of Neutrino Factory [9].

References

1. OPERA Collaboration, M. Guler et al.: Experiment proposal, CERN-SPSC-2000-028 and LNGS P25/2000 (2000); Status Report on the OPERA experiment, CERN-SPSC-2001-025 and LNGS-EXP 30/2001 (2001)
2. CHOOZ Collaboration, M. Apollonio et al.: Phys. Lett. B **466**, 415 (1999)
3. G. Acquistapace et al.: CERN 98-02 and INFN/AE-98/105 (1998); R. Bailey et al.: "Addendum to Report CERN 98-02",CERN-SL 99-034 and INFN/AE-99/05 (1999); A.E. Ball et al.: SL-Note 2000-063 (2000)
4. R. Cappi et al.: CERN-SL-2001-032 (2001)
5. K. Kodama et al.: Phys. Lett. B **504**, 218 -224 (2001); S. Aoki for the DONUT and CHORUS experiments: Nucl. Instrum. Meth. A **473**, 192–196 (2001)
6. S. Bondil et al.: submitted to Nucl. Instrum. Meth.
7. Y. Hayato's talk in this proceeding.
8. M. Komatsu, P. Migliozzi, F. Terranova: J. Phys. G **29**, 443 (2003)
9. D. Autiero et al.: hep-ph/0305185