First Events from the CNGS Neutrino Beam detected in the emulsion target of the OPERA experiment

Alberto Marotta - INFN Napoli on behalf of the OPERA collaboration
“Neutrino oscillations”

Pontecorvo, 1957
Maki, Nakagawa and Sakata, 1962
Pontecorvo and Gribov, 1969

• A phenomenon induced by $m_\nu > 0$
• Implies the apparent “metamorphosis” of a $\nu$ into a different one (e.g. $\nu_\mu \rightarrow \nu_\tau$)
• The most sensitive method to measure $\Delta m_\nu^2$

The PMNS matrix

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

Terms probed by next experiments

Atmosferic

CP violation phase

Solar, reactor analysis

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Atmospheric neutrino oscillations: status of the art

SK I + II $P_{\nu\tau} = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 L}{E}\right)$

$\Delta \chi^2 (\text{decoherence}) = 4.8\sigma$

$\Delta \chi^2 (\text{decay}) = 5.3\sigma$

SK I: 1489 days
SK II: 804 days
$\begin{cases} 23,000 \text{ V's} \\ 100 \text{ MeV} - 10 \text{ TeV} \end{cases}$

$\sin^2 2\theta > 0.93$ (90% C.L.)

best fit: $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta = 1$

still missing: direct observation of oscillated $\nu_\tau$'s

SK oscillation signal confirmed by K2K and MINOS

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The Oscillation Project with Emulsion Tracking Apparatus

- Provide unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the parameter region indicated by atmospheric neutrino data

- Long baseline experiment searching for $\nu_\tau$ appearance in a pure $\nu_\mu$ beam (CNGS beam, $<E> = 17$ GeV, $L = 732$ km)

- Hybrid set-up (nuclear emulsions + electronic detectors)

- Detection of $\nu_\tau$ CC interactions and direct observation of $\tau$ decays
To identify $\tau$ leptons, “see” their decay topology

The challenge

$\nu$ oscillation $\rightarrow$ massive AND decay topology $\rightarrow$ micron

The ECC also provides:
- electron detection for $\tau \rightarrow e$ decays and search for $\nu_\mu - \nu_e$ appearance
- momentum measurement by multiple scattering

Lead – nuclear emulsion sandwich
“Emulsion Cloud Chamber”, in brief “ECC”
CNGS overview

\[ N_\tau = N_A M_D \int \phi_{\nu_\mu} (E) P_{\nu_\mu \to \nu_\tau} (E) \sigma_{\nu_\tau}^{CC} (E) \sigma (E) dE \]

**Beam main features**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L)</td>
<td>730 km</td>
</tr>
<tr>
<td>(&lt;E_{\nu})&gt;</td>
<td>17 GeV</td>
</tr>
<tr>
<td>(L/\langle E_{\nu}\rangle)</td>
<td>43 km/GeV</td>
</tr>
<tr>
<td>((\nu_e + \overline{\nu}<em>e)/\nu</em>\mu)</td>
<td>0.87%</td>
</tr>
<tr>
<td>(\overline{\nu}<em>\mu/\nu</em>\mu)</td>
<td>2.1%</td>
</tr>
<tr>
<td>(\nu_\tau) prompt</td>
<td>negligible</td>
</tr>
</tbody>
</table>

"Off peak" Limiting for \(\nu_\mu \leftrightarrow \nu_e\) searches

Event rate for OPERA (~1.3kton) with \(4.5 \cdot 10^{19}\) pot (200 days/year)

~ 6200 evt/year (CC + NC)

~ 25 \(\nu_\tau\)CC/year for \(\Delta m^2 = 2.4 \cdot 10^{-3}\) eV\(^2\)

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Laboratori Nazionali del Gran Sasso - INFN
Largest underground laboratory for astro-particle physics

Research lines

- Neutrino physics (mass, oscillations, stellar physics)
- Dark matter
- Nuclear reactions of astrophysics interest
- Gravitational waves
- Geophysics
- Biology

- 1400 m rock coverage
- cosmic $\mu$ reduction = $10^{-6}$ (1/m$^2$h)
- underground area: 18 000 m$^2$
- external facilities
- easy access
- 756 scientists from 25 countries
- Permanent staff = 66 positions

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**Target:**
- Lead/emulsions bricks alternated to scintillator strips
- Emulsion tracking resolution:
  - $\delta x < 1 \mu m$, $\delta \theta < 1 mrad$
- 154750 bricks = ~ 1.3 kton

**Emulsion layers**
- 1 brick = 56 layers of Pb & emulsion

**Muon Spectrometer:**
- Vertical drift tubes for $\mu$ p measurement from deflection through 24 magnetized iron slabs.
- Magnet instrumented with 22 RPC plane
- $\Delta p/p \sim 20\%$ up to 50 GeV, charge miss-ID < 0.3%
**Lead - Emulsion target**

Total target mass: \(~1300\)t
(154750 bricks, 9 M emulsions and Pb plates)

- **brick** (target unit)
  - 56 Pb plates + 57 emulsions

- **Micro-metric space resolution**
  - (Emulsion) + target mass (Lead)

- **Compact and modular structure**

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Brick Assembly Machine

Robots will pile up bricks at a rate of $\sim 700$ bricks / day
Brick Manipulator System

Robot for brick insertion (target filling) and removal (during run)

Ventouse Vehicle

Carousel mechanism

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A picture of the OPERA detector

SM1

Veto
Target tracker
BMS

SM2

Spectrometer:
XPC, HPT, RPC, magnet

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One Event in OPERA

Electronic detectors

→ select $\nu$ interaction brick and CS
→ $\mu$ ID, charge and $p$

Emulsion analysis

→ vertex search
→ decay search
→ $e/\mu$ ID, kinematics

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Automatic Emulsion Scanning

Off-line Data Taking

~ 30 bricks will be daily extracted from target and analyzed using high-speed automatic systems
Several labs distributed in Europe and Japan

European Scanning System

scanning speed ~ 20 cm² / h

Customized commercial optics and mechanics + asynchronous DAQ software

S-UTS (Japan)

High speed CCD Camera (3 kHz)

Piezo-controlled objective lens

Synchronization of objective lens and stage

Constant speed stage

Hard-coded algorithms

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Field of view

16 tomographic images

40 μm emulsion sheet

2D Image processing

3D reconstruction of particle tracks

Passing-through tracks rejection

Track segments found in 8 consecutive plates

Vertex reconstruction

Momentum measurement by Multiple Scattering
dE/dx for π/μ separation at low energy
Electron identification and energy measurement

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Search for $\nu_\mu \rightarrow \nu_\tau$ oscillation: expected number of events

<table>
<thead>
<tr>
<th>$\tau$ decay channels</th>
<th>$\Delta m^2 = 2.4 \times 10^{-3}$ eV$^2$</th>
<th>$\Delta m^2 = 3.0 \times 10^{-3}$ eV$^2$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>2.9</td>
<td>4.2</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \rightarrow e$</td>
<td>3.5</td>
<td>5.0</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \rightarrow h$</td>
<td>3.1</td>
<td>4.4</td>
<td>0.24</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>0.9</td>
<td>1.3</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td><strong>10.4</strong></td>
<td><strong>15.90</strong></td>
<td><strong>0.76</strong></td>
</tr>
</tbody>
</table>

Main background sources:
- charm production and decays
- hadron re-interactions in lead
- large-angle muon scattering in lead

*full mixing, 5 years run @ 4.5x10$^{19}$ pot / year*
OPERA sensitivity

OPERA Discovery probability vs $\Delta m^2$

Exclusion plot at 90% C.L.

- 4-$\sigma$ evidence
- 3-$\sigma$ evidence

$\Delta m^2 \left(10^{-3} \text{ eV}^2\right)$

$10^{-2}$

$10^{-3}$

$0$ $0.1$ $0.2$ $0.3$ $0.4$ $0.5$ $0.6$ $0.7$ $0.8$ $0.9$ $1$

$\sin^2 2\theta_{\mu\tau}$

OPERA 75% mass (90% C.L.)

SK+K2K+CHOOZ +MINOS 2006 (1$\sigma$, 2$\sigma$, 3$\sigma$)

OPERA 100% mass (90% C.L.)

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September 24th to October 22nd: first OPERA Physics run

CNGS run parameters

On October 3rd OPERA observed the first event in the target

During the run we have accumulated $0.0824 \times 10^{19}$ pot onto the target with a mean value of $1.8 \times 10^{13}$ proton per extraction: this represents $\sim 3.6$ effective days for the run!
Time Selection of Beam Events

GPS Time Stamp resolution ~ 100 ns
Events Time Structure

- Beam events are selected correlating OPERA selected events with GPS time information with CERN beam spill time.

- 319 events on time.

- Cosmic ray background.

- Extraction length = 10.5 μsec.
Angular distribution of all events

Angle w.r.t. horizontal

Cosmic $\mu$: mountain rock structure asymmetry coherently with previous MACRO observation

Zoom on Beam events Coming 3.5° from below

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Data analysis and event selection

Data are extracted from the DAQ data base every 12 hours and processed with the OPERA reconstruction package.

*In time* events are selected and stored on a dedicated file.

Then *in time* events are scanned visually and stored by categories:
- magnet interaction
- rock muon
- *in target* CC and NC like (according to the muon id)

The interactions in the material surrounding OPERA target are analysed separately and are used for the monitoring on the CNGS beam and of the OPERA detector
Beam events

CC event originated upstream of the detector (BOREXINO, rocks)

CC event originated in the first magnet
Data analysis and event selection

We have selected and analysed 365 events;

331 of them passed through the analysis cuts;

The number of expected events was 303;

The observed/expected events ratio is very close to what measured last year, so we conclude that the CNGS beam has been operated in the same condition;
Data analysis and event selection

Main physical distribution for the selected events

The Vertex location is defined as the first hit of the 3D reconstructed track

The vertical angle of the track.
Fit: 3.4±0.2 degree

The Energy of the muon as measured with the RPC of the spectrometer
In target events analysis

We have observed 38 events (31.5 expected) in the emulsion target area

- 22 charged current
- 9 neutral current

compatible with the relative cross sections

The events are analysed through the **brick finding** package:
- a neural network for the wall finding
- the hadronic shower parametrization
- the exact configuration and alignment of the target at the time of the event taking into account the wall elongation as a function of the filling
- the probability estimate for the vertex location in each brick
In target events analysis

CC like event analysis:

NC like event analysis:
Kink of Track 1 between plates 33 and 34

Flight length of the parent track ~ 5 mm
Kink analysis

\[ \theta = 0.031 \text{ rad} \]

Daughter track momentum estimated by MCS

\[ P = 3.1 \pm 0.7 \text{GeV} \]

Elastic or inelastic scattering?

\[ P_T = 96 \pm 20 \text{MeV} \]

Kink due to hadronic interactions

(KEK measurement)

PRELIMINARY!!!
EVENT ID 179673325

quasi-elastic-like topology

$IP_\mu = 0.33 \, \mu m$

$SlopeX = -0.040$

$SlopeY = 0.014$

$IP_h = 4.50 \, \mu m$

$SlopeX = -0.380$

$SlopeY = -0.602$
Event analysis

**Muon** $P = 21.8$ GeV (spectrometer)

**Hadron** $p\beta = 308 \pm 50$ MeV

**Pion hypothesis** $p = 331 \pm 54$ MeV, $\beta = 0.93$

**Proton hypothesis** $p = 583 \pm 95$ MeV, $\beta = 0.53$

Emulsions permit energy loss measurement of charged particles by counting the number of grains produced by ionizations.

Energy loss measurement suggest that pion is most probable hypothesis for the hadron track.
EVENT ID 178969961

<table>
<thead>
<tr>
<th>Tk</th>
<th>Slope</th>
<th>CS tk</th>
<th>Stop</th>
<th>IP (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-0.028, 0.095</td>
<td>6</td>
<td>57</td>
<td>5.2</td>
</tr>
<tr>
<td>B</td>
<td>-0.114, 0.143</td>
<td>(7?)</td>
<td>57</td>
<td>0.3</td>
</tr>
<tr>
<td>C</td>
<td>0.091, 0.009</td>
<td></td>
<td>57</td>
<td>6.2</td>
</tr>
<tr>
<td>D</td>
<td>-0.166, -0.342</td>
<td>32</td>
<td>21.4</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0.127, 0.075</td>
<td>35</td>
<td>16.4</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>-0.370, 0.430</td>
<td>28</td>
<td>15.3</td>
<td></td>
</tr>
<tr>
<td>Shower</td>
<td>0.019, -0.006</td>
<td>2.8</td>
<td>38</td>
<td>-</td>
</tr>
</tbody>
</table>

Tk Slope CS tk Stop IP (μm)

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Conclusions

✓ The main aim of the OPERA experiment is to unambiguously confirm/disproof the $\nu_\mu \leftrightarrow \nu_\tau$ atmospheric oscillation channel;
✓ The first physics run started the 24th of September and ended the 22nd of October;
✓ The whole chain from data acquisition to event analysis worked properly. The OPERA concept has been fully proved.
✓ Some typical events have been shown.
✓ The studies on the acquired events is going on.
✓ And now... we wait for the next physics run and the appearance of the 1st $\tau$ !!!
**Target Tracker**

Plastic scintillator strips (AMCRYSH6 7 2 6 1) readout by Kuraray WLS fibres + Hamamatsu PMT’s (64 channels)

**Target Tracker tasks**

- **Trigger:** $\epsilon > 99\%$
- **Initiate muon tagging**

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Muon spectrometer

μ identification: ε > 95%
Δp/p < 20%, p < 50 GeV/c
misidentified μ charge prob. < 0.3%

Inner Tracker
11 + 11 planes of RPC’s
21 bakelite RPC’s (2.9x1.1m²) / plane
• muon identification (TT)
• range measurement

Precision Tracker
6 planes of drift tubes
space resolution: ~300μm
• momentum measurement
Brick handling and processing

brick confirmation by finding the tracks associated to the interaction inside the Changeable Sheet doublet (CSd)

- if the event is not confirmed in the most probable brick, the processing of the CSd for the next one is organized;
- if the brick is confirmed by the CSd results the brick is sent in the brick processing chain.

Brick processing chain

- confirmed bricks are exposed to cosmics used for plate to plate alignment
- developed
- shipped to laboratories for scanning and analysis

<table>
<thead>
<tr>
<th>IN PROGRESS...</th>
<th>Europe</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allocated events</td>
<td>19 (15 CC + 4 NC)</td>
<td>19 (14 CC + 5 NC)</td>
</tr>
<tr>
<td>Event confirmed in the CSd</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Located events in the bricks (scanning in progress...)</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>