Measurement of Neutrino Oscillations with ANTARES

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The ANTARES Site & Infrastructure

IFREMER Toulon Centre

Shore Station

FOSELEV Marine

40 km submarine cable
2006 – 2008: Construction of the Detector

- Junction box 2001
- Main cable 2002
- Line 1, 2 2006
- Line 3, 4, 5 01 / 2007
- Line 6, 7, 8, 9, 10 12 / 2007
- Line 11, 12 05 / 2008

~70 m
The ANTARES Detector

- 885 10inch PMTs
- 12 lines
- 25 storeys / line
- 3 PMTs / storey

40 km to shore

450 m

Junction Box

Interlink cables

885 10inch PMTs
12 lines
25 storeys / line
3 PMTs / storey
The high-energy universe

- Supernova remnants (SN1006, optical, radio, X-ray)
- Active galactic nuclei (artist’s view)
- Pulsars (Crab, X-ray, Chandra)
- Gamma-ray bursts (GRB 080319B, X-ray, SWIFT)

Galactic

Extra-Galactic
Hydrophone: acoustic positioning

Optical Beacon with blue LEDs: *timing calibration*

- NIM A578 (2007) 498
- Astrop. Phys 34 (2011) 539

Titanium frame: *support structure*

Optical Module: 10” Hamamatsu PMT in 17” glass sphere *photon detection*

- NIM A484 (2002) 369
- NIM A555 (2005) 132

Local Control Module (Ti): *Front-end ASIC, DAQ/SC, DWDM, Clock, tilt/compass, power distribution...*

- NIM A570 (2007) 107
- NIM A622 (2010) 59

Hydrophone: acoustic positioning

Optical Beacon with blue LEDs: *timing calibration*
Muon tracks in the detector

- Muons detected per year (Antares)
  - Atmospheric $\mu$
    $7 \times 10^8 = 20$ Hz
  - Atmospheric $\nu \rightarrow \mu$
    $2 \times 10^3 = 5$ per day
  - Cosmic $\nu \rightarrow \mu$ few
upward $\mu$ from CC $\nu_\mu$ interactions

ANTARES, clean sample of $\nu_\mu$ isolated (2008)
Reconstruction Concept

Zenith : 65.5
Fit on 3 line(s)

Run 29414 Frame 14218
Mon Sep 10 17:44:08 2007
Trigger bits 80000021
Line 1-5 Physics Trigger (L)

1 2 3 4 5 6 photons

Line 1
Line 2

Line 5
Line 3

Line 4
Line 6

time (nsec)

 height (mm)
1. Select “hot spots” at each detector string

should correspond to point of closest approach of muon and det. line

Zenith:  65.5
Fit on 3 line(s)
2. Add hits from adjacent storeys

Use narrow causality time window here

Zenith: 65.5
Fit on 3 line(s)
3. Perform track fit

Use selected hits (time & amplitude) & simplified geometry

Zenith: 65.5
Fit on 3 line(s)
Clean low energy single-line event

Close to vertical

Zenith: 9.8°
Fit on 1 line
Good fit

No correlated activity in any other line
Clean low energy single-line event

Point of closest approach

7 storeys hit
8 storeys high
100m = 20 GeV
Total signal: 17 p.e.
Oscillations with Atmospheric Neutrinos

For upgoing tracks
$L = 2 \times R_{\text{Earth}} \times \cos \Theta$

Oscillations maximal at 24 GeV for vertical neutrinos (~120m):

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2 \left( \frac{1.27 \Delta m_{32}^2 L}{E_\nu} \right) = 1 - \sin^2 2\theta_{32} \sin^2 \left( \frac{16200 \Delta m_{32}^2 \cos \Theta}{E_\nu} \right)$$
Oscillations with Atmospheric Neutrinos

Large effect
single-line events: low energy, vertical

Small effect
multi-line events: higher energy, isotropic

MC truth

Solid
No oscillations
Dashed
Oscillations PDG
Neutrino Oscillations: Track Selection

Select pure sample of atmospheric neutrinos (<5% muon contamination)
Require upgoing tracks with more than 7 storeys hit
Special low energy fit – do not fit azimuth
zenith angle resolution : 3 degrees

Single-line events

Atm. muons
Oscillations PDG
No oscillations
data
Neutrino Oscillations: Track Selection

Select pure sample of atmospheric neutrinos (<5% muon contamination)
Require upgoing tracks with more than 5 storeys hit
More than 9 degrees from horizon
zenith resolution 0.8 degrees

Multi-line events

Atm. muons
Oscillations PDG
No oscillations
data
Event Reduction

- 2007 to 2010; 863 days of active time
- Good agreement data/MC on all cut levels
- Efficiency w.r.t. trigger 23% (ML) and 7% (1L)
- Small but measurable reduction due to oscillations
- Effect more pronounced for single-line sample

<table>
<thead>
<tr>
<th></th>
<th>Multi-line</th>
<th>Single-line</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>data</td>
<td>ν MC</td>
<td>μ MC</td>
</tr>
<tr>
<td>Triggered</td>
<td>1.42 $10^8$</td>
<td>8755</td>
<td>1.23 $10^8$</td>
</tr>
<tr>
<td>Nstorey cut</td>
<td>1.33 $10^8$</td>
<td>8248</td>
<td>1.18 $10^8$</td>
</tr>
<tr>
<td>Upward</td>
<td>2.74 $10^6$</td>
<td>5512</td>
<td>1.84 $10^6$</td>
</tr>
<tr>
<td>Fit quality</td>
<td>1632±40</td>
<td>1971±6</td>
<td>52±12</td>
</tr>
<tr>
<td></td>
<td>1910±6</td>
<td>52±12</td>
<td>494±22</td>
</tr>
</tbody>
</table>
Preliminary contour from event ratio

Data: \[ R = \frac{494}{1632} = 0.303 \pm 0.015 \]

MC Non-Osc: \[ R = \frac{651}{1971} = 0.330 \]

Non-oscillation hypothesis at 2.1 sigma from measured ratio

\[ \delta N1/N2 : 5.0\% \]
\[ \delta \Delta m^2 : 37\% \]
Zenith angle only

- Effect of oscillation in first two bins
- close to vertical

\[ \Delta m^2 = (3.0-0.9+1.4) \times 10^{-3} \text{ eV}^2 \]
Energy reconstruction

• Derived from approximative muon range

\[ S = \frac{(z_{\text{max}} - z_{\text{min}})}{\cos \Theta_R} \]

\[ E_R = S \cdot 0.2 \text{ GeV/m} \]
Energy Resolution

• Zenith angle resolution (median, neutrino)
  – Multiline events : 0.8°
  – Single line events : 3.0°

• Energy resolution for $E < 100$ GeV :
Total Normalisation Affects 1L and ML in the same way
Systematics

Changes of histogram shape
Affects 1L and ML differently
Modifies ratio $R = 1L/ML$

Similar to effect of oscillations
Systematics

\[ \chi^2 = \sum_i \left[ N_i - (1 + \epsilon)MC_{iL}^{1L} - (1 + \eta)MC_{iL}^{ML} \right]^2 / \sigma_i^2 + (\epsilon - \eta)^2 / \sigma_R^2. \]

Absolute normalisation not constrained
Individual pull factor for both event samples
  Absorption length: ±10%
  Detector efficiency: ±10%
  Spectral index of ν flux: ±0.03
  OM angular acceptance
  Cut values varied \(\rightarrow\) analysis stability
Results in \(\sigma_R=5\%\) - relative pull between samples
Final distribution - $E/cos\theta$

- Cutoff at 20 GeV
- $E_\nu > 20$ GeV corresponds to 8 storey
- Effect of oscillations in 7-8 leftmost bins

$\epsilon = 0.138$
$\eta = 0.143$

No oscillations
Best fit
Data
Result

No oscillation

$\chi^2/NDF = 40/24 \ (2.1\%)$

Best fit

$\chi^2/NDF = 17.1/21$

$\Delta m^2 = 3.1 \times 10^{-3} \text{ eV}^2$

$\sin^22\theta = 1.00$

No oscillations

Best fit data

$\varepsilon = 0.138$

$\eta = 0.143$
First measurement of oscillation parameters with high energy neutrino telescope

Assuming maximal mixing: $\Delta m^2 = (3.1 \pm 0.9) \times 10^{-3} \text{ eV}^2$

Published in PLB 714 (2012) 224
Sanity check – Contour Stability

- Change of spectral index of 0.03

\[ \Delta m^2/(10^{-3}\text{eV}^2) \]
Contribution from cascades

**Single line sample**

- Contribution: 6 events
- Reminder Atm muons: 28

**Multi line sample**

- Contribution: 1 events
- Reminder Atm muons: 52
Results

Shown in plot:
Best Fit
No oscillations

<table>
<thead>
<tr>
<th></th>
<th>Best Fit</th>
<th>PDG</th>
<th>No osc.</th>
<th>No osc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$</td>
<td>17.1/21</td>
<td>18.4/21</td>
<td>31.1/23</td>
<td>40.0/24</td>
</tr>
<tr>
<td>$\Delta m^2$</td>
<td>3.06</td>
<td>2.43</td>
<td>---</td>
<td>---</td>
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<tr>
<td>$\sin^2 2\theta$</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>-0.138</td>
<td>-0.180</td>
<td>-0.302</td>
<td>-0.225</td>
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<tr>
<td>$\eta$</td>
<td>-0.142</td>
<td>-0.162</td>
<td>-0.196</td>
<td>-0.225</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>0.4%</td>
<td>2.2%</td>
<td>11.5%</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Tau Neutrino appearance?

- Oscillations reduce data sample by **155 events** (1L: 94; ML: 61)
- $\nu_\tau$ CC cross section lower (threshold)
- 83% cascade like events
  - Cascade-like events effectively suppressed (<1 event remaining)
- 17% branching ratio into muons
  - Muon energy lower compared to $\nu_\mu$
  - <5 events (3%)
Lowering energy threshold?

- Nstorey > 7: hard cut to suppress muons
- tchi2 < 0.95
- Nstorey == 7 might be usable in future analyses