XXth International Seminar on High Energy Physics “Quarks-2018”
Valday, Russia
May 27 – June 2, 2017

KM3NeT:
neutrino oscillation and astroparticle research
in the Mediterranean sea

Dmitry Zaborov
(CPPM / Aix-Marseille Univ., Marseille, France)
on behalf the KM3NeT collaboration
Contents

1) Introduction to KM3NeT

2) KM3NeT / ORCA

3) Current status

4) Potential of a neutrino beam from Protvino to ORCA
Neutrino telescopes around the world

ANTARES

KM3NeT

This talk

Baikal

See talk by Z. Dzhilkibaev

IceCube

commons.wikimedia.org
Neutrino detection principle

Sea water =

target material for $\nu$ interactions

+ Cherenkov radiator

Mediterranean deep-sea water

Light absorption length: $\approx 60 \text{ m}$

Light scattering length: $\sim 260 \text{ m}$

ANTARES

875 optical modules on 12 strings
Completed in 2008
Operating for 10 yr now

All-flavour neutrino search, Phys. Rev. D 96, 082001 (2017)

GW 171807 (NS-NS merger)


... and many other results
KM3NeT sites and participating countries

A distributed research infrastructure at two sites

Cities and Sites of KM3NeT

Oscillation Research with Cosmics In the Abyss

3400 m ARCA

* KM3NeT = km³ Neutrino Telescope

Single Collaboration, Single Technology

Astroparticle Research with Cosmics In the Abyss

May 28, 2018

D. Zaborov - KM3NeT
From ANTARES to KM3NeT: Optical Module

ANTARES
Optical Module (OM)

- 10” PMT
- HV base
- LED

KM3NeT
Digital Optical Module (DOM)

- 31 x 3” PMTs
- PMT HV
- LED & piezo
- FPGA readout
- White Rabbit
- DWDM

- Uniform angular coverage
- Directional information
- Digital photon counting
- All data to shore

photocathode area similar to a 17” PMT
From ANTARES to KM3NeT: detector storey

ANTARES storey

- 3 OMs
- electronics container (Ti)
- frame (Ti)

KM3NeT storey

- 1 DOM

Sensitivity ~ 2x - 3x ANTARES OM

Compact structure minimizes bioluminescence (stimulated by drag)
From ANTARES to KM3NeT: detector string

ANTARES string

KM3NeT Detection Unit (DU, string)
From ANTARES to KM3NeT: deployment method

- Rapid deployment
- Autonomous unfurling
- Multiple DUs can be deployed in one sea operation

Watch [https://www.youtube.com/watch?v=tR8jwgG6uzk](https://www.youtube.com/watch?v=tR8jwgG6uzk)
KM3NeT - ORCA

Key mission: determine neutrino mass hierarchy

8 Mt instrumented
115 strings
18 DOMs / string (50 kt)
31 PMTs / DOM (3 kt)
Total: 64,000 PMTs

Digital Optical Module

Depth = 2450 m

May 28, 2018

Optical background (mainly $^{40}$K): 10 kHz/PMT
KM3NeT - ARCA

- **2 x 115** strings
- **18** DOMs / string
- **31** PMTs / DOM
- Total: **128 000 PMTs (3″)**

- Vertical spacing: 36 m
- Horizontal spacing: 90 m

**Mission: neutrino astronomy**

- Angular resolution ~ 0.2 deg (tracks, E > 10 TeV)
- Energy resolution up to 5% (cascades)
- Sensitivity similar to IceCube, but covering both sky hemispheres
Instrumented volume

Smaller but denser instruments are best for low energies (low amount of light)

Larger but sparser instruments are best for high energies (low fluxes)

SuperK
11100 PMTs
50 kt
41 m
MeV - GeV
Solar & atm. \( \nu \)
operating for 20 yr

KM3NeT-ORCA
2000 OMs
8 Mt
200 m
E > 3 GeV
atm. \( \nu \)
under construction

ANTARES
885 PMTs
20 Mt
400 m
E > 20 GeV
astrophysical and atm. \( \nu \)
operating for 10 yr

KM3NeT-ARCA
4000 OMs (128 000 PMTs)
1 Gt
1000 m
E > 100 GeV
astrophysical \( \nu \)
under construction

IceCube & Baikal-GVD have similar size
1) Introduction to KM3NeT

2) KM3NeT / ORCA

3) Current status

4) Potential of a neutrino beam from Protvino to ORCA
Neutrino mass hierarchy (ordering)

Normal hierarchy (NH)

\[ m^2 \]

\[ \Delta m^2_{\text{solar}} \]: sign known

\[ \Delta m^2_{\text{atm}} \]

Inverted hierarchy (IH)

\[ m^2 \]

\[ \Delta m^2_{\text{atm}} \]

\[ \Delta m^2_{\text{sol}} \]: sign unknown

Important for theory, 0νββ, ...

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D. Zaborov - KM3NeT
Mass hierarchy with atmospheric neutrino

- Known composition ($\nu_e, \nu_\mu$)
- Wide range of baselines (50 - 12800 km) and energies (GeV - PeV)
- Oscillation affected by matter (mass hierarchy-dependent): maximum difference IH / NH at $\theta=130^\circ$ (7645 km) and $E_\nu = 7$ GeV
- Opposite effect on anti-neutrinos: IH ($\bar{\nu}$) $\approx$ NH(anti-$\nu$) but differences in flux and cross-section:
  \[ \Phi_{\text{atm}}(\nu) \approx 1.3 \times \Phi_{\text{atm}}(\text{anti-}$\nu$) \]
  \[ \sigma(\nu) \approx 2\sigma(\text{anti-}$\nu$) \text{ at low energies} \]
ORCA effective mass

After triggering, atmospheric muon rejection and containment cuts

- Energy threshold determined by DOM spacing
- 1 Mton @ 3 GeV
- 6 Mton @ 10 GeV

Events/yr:
- $\nu_e$ CC: 17,300
- $\nu_\mu$ CC: 24,800
- $\nu_\tau$ CC: 3,100
- NC: 5,300
Particle ID

SHOWER-like events

EM cascade

τ decay products

Hadronic shower

τ
ν

Hadronic shower + muon track

CC

νₑ

hadronic shower

νµ

hadronic shower

NC

ν

hadronic shower

ARCA simulated event (ORCA similar)

KM3NeT

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Particle ID performance

Track / Shower event classification

At 10 GeV:
- 90% correct ID of $\nu_e^{\text{CC}}$
- 70% correct ID of $\nu_\mu^{\text{CC}}$
Zenith angle resolution

Showers

Tracks

~ 5° error on zenith for 10 GeV neutrinos for both track and shower channels

Limited by interaction kinematics (neutrino – lepton angle)
Energy resolution better than 30% in relevant range

Distribution close to Gaussian
## Sensitivity to Mass Ordering

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</table>

![Graph](image)

**Worst case:** 3 sigma in 4 years  
**Best case:** $>5$ sigma in 3 years  
(NH & upper octant of $\theta_{23}$)

Recent T2K result on $\theta_{23}$:  
\[
\sin^2\theta_{23} = 0.55^{+0.05}_{-0.09} (0.55^{+0.05}_{-0.08})
\]  
(arXiv:1707.01048)
Other ORCA science topics

- Precision measurement of neutrino mixing parameters (2% on $\Delta m^2_{23}$ and 4-10% on $\sin^2 \theta_{23}$)
- Sterile neutrino & non-standard interactions
- Earth tomography and composition
- Supernova monitoring
- Indirect search for Dark Matter
- Low energy (GeV-TeV) neutrino astrophysics
1) Introduction to KM3NeT

2) KM3NeT / ORCA

3) Current status

4) Potential of a neutrino beam from Protvino to ORCA
News from first ARCA Detection Units

- Optical Module at Antares site, April 2013
- Mini string (3 DOMs) at ARCA site, May 2014
- First full Detection Unit at ARCA site, Dec 2015
  - One more DU added in May 2016

Event rate (atmospheric muons)
News from the first ORCA Detection Unit deployed in September 2017

Number of events (upgoing):
MC atm neutrinos : 8.33
MC atm. muons    : ~ 1
observed              : 13

Analysis optimized for vertical upgoing tracks (horizontal tracks suppressed)
A neutrino candidate from ORCA DU-2

Energy ~ 10 GeV
1) Introduction to KM3NeT

2) KM3NeT / ORCA

3) Current status

4) Potential of a neutrino beam from Protvino to ORCA
P2O : Protvino to ORCA

- Baseline 2588 km; beam inclination: 11.7° ($\cos \theta = 0.2$)
- Deepest point 134 km: 3.3 g/cm3
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CP violation

arXiv:1803.08017
Protvino accelerator complex
(100 km South of Moscow)

U-70 accelerator constructed in 1967
Now operates at 8 - 15 kW

1-turn fast extraction:
5 μs spill every 9 s

Operated by NRC «Kurchatov Institute» – Institute for High Energy Physics (IHEP), Protvino
Possible location of the neutrino beam line

Bend of proton beam in:
horizontal plane – 21.7°
vertical plane – 11.8°

~ 90 m of 1.6 T magn. field

Max. depth (with respect to the beam level in U70):
target hall – 8 m
beam dump – 32 m
near detector – 60 m
Simulated Neutrino Beam

Beam spectra from V. Garkusha, F. Novoskoltsev & A. Sokolov, *Study of Neutrino Oscillations with the U-70 Accelerator Complex, IHEP Preprint 2015-5* – beam optimized for Protvino-Gran Sasso (on-axis)

Focus $\pi^+$ (Neutrino beam)

Beam power : 450 kW, $4 \times 10^{20}$ p.o.t. per year

(for reference: Fermilab-Nova beam is 700 kW)
Expected neutrino rates in ORCA
normal mass hierarchy

Vacuum oscillation maximum at $E = 5.1$ GeV
Most $\nu_\mu$ convert to $\nu_\tau$ which remains largely invisible (CC reaction suppressed by $\tau$ mass)
$\nu_\mu \rightarrow \nu_e$ transitions are enhanced by the MSW effect, resonance energy 3.8 GeV

For comparison:
DUNE: ~ 250 $\nu_e$ events / yr

After 3 yr of 450 kW beam:
$\nu_\mu$ CC: ~ 30000 events
$\nu_e$ CC: ~ 8000 events
$\nu_\tau$ CC: ~ 3500 events
NC: ~ 6000 events
Sensitivity to CP violation

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \times \begin{pmatrix}
c_{13} & 0 & e^{-i\delta_{13}} \\
0 & 1 & 0 \\
-e^{i\delta_{13}} & 0 & c_{13}
\end{pmatrix} \times \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

2.5 sigma after 3 years of 450 kW beam
or 15 years of 90 kW beam

KM3NeT/P2O preliminary

Competitive with DUNE!

DUNE CDR
arXiv:1601.05471
Measurement accuracy of $\delta_{CP}$

NB: this study uses preliminary estimates of systematic uncertainties
P2O sensitivity to mass hierarchy

> 5 sigma after 1 year of 450 kW beam
(or 5 years of 100 kW beam)
Summary

- KM3NeT-ARCA will explore the high energy neutrino sky with an unprecedented sensitivity
- KM3NeT-ORCA aims at determining the neutrino mass hierarchy after 3 years of operation
- Both ORCA and ARCA are now under construction
- A neutrino beam from Protvino to ORCA is a promising venue to study leptonic CP violation (competitive with DUNE, T2HK)
Learn more about KM3NeT


- [http://www.km3net.org/](http://www.km3net.org/)
Backup slides
ORCA schedule and funding

Total ORCA cost $\approx 45$ M€

Phase 1: 7 strings – 11 M€

Phase 2: 115 strings – fund requests ongoing

Outlook

ORCA will determine the NMO in 3 years with at least $3\sigma$ significance
ORCA sensitivity to $\Delta m^2_{32}$ and $\sin^2\theta_{23}$

- High statistics and excellent resolution → Measure $\Delta m^2_{32}$ and $\sin^2\theta_{23}$
- Competitive with NOvA and T2K projected sensitivity in 2020
- Expect 2-3% precision in $\Delta m^2_{32}$ and 4-10% in $\sin^2\theta_{23}$
Optimal baseline

- Optimal baseline to measure mass hierarchy with beam neutrinos is between 2000 km and 4000 km
- Degeneracy between MH and $\delta_{\text{CP}}$ for $L < 1000$ km
- Peak energy follows initially first oscillation maximum at $E = 25$ GeV * $\cos\theta$
- Levels off at mantle resonance energy ($\sim 6$ GeV)
Expected neutrino rates in ORCA
normal mass hierarchy

Raw event numbers in ORCA

Calculations with GloBES

Protvino to ORCA
12 $\cdot$ $10^{20}$ POT

Neutrino beam
Normal mass hierarchy

νμ CC: ~ 30000 events
νe CC: ~ 8000 events
ντ CC: ~ 3500 events
NC: ~ 6000 events

For comparison:
DUNE: ~ 900 $\nu_e$ events / yr

Vacuum oscillation maximum at $E = 5.1$ GeV
Most $\nu_\mu$ convert to $\nu_\tau$ which remains largely invisible (CC reaction suppressed by $\tau$ mass)
$\nu_\mu \rightarrow \nu_e$ transitions are enhanced by the MSW effect, resonance energy 3.8 GeV

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Expected neutrino rates in ORCA
inverted mass hierarchy

Raw event numbers in ORCA

Protvino to ORCA
$12 \cdot 10^{20}$ POT

Neutrino beam
Inverted mass hierarchy

Calculations with GloBES

$\nu_\mu$ CC: $\sim$ 30000 events
$\nu_e$ CC: $\sim$ 2000 events
$\nu_\tau$ CC: $\sim$ 3700 events
NC: $\sim$ 6000 events

$\nu_\mu \rightarrow \nu_e$ transitions suppressed by the MSW effect

If inverted mass hierarchy is true, switch to anti-neutrino beam (for CPV studies)
Multi-Parameter fit of simulated data

- Combined fit of nuisance and oscillation parameters
- No neutrino/anti-neutrino skew
- No spectral index skew
- No energy scale shift

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<th>Parameter</th>
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<th>Start value</th>
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<td>$\theta_{13}$</td>
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<td>$\theta_{23}$</td>
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<td>$\Delta M^2$ [eV$^2$]</td>
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<td>2.44 10^{-3}</td>
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<tr>
<td>$\delta_{CP}$</td>
<td>many</td>
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<table>
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<th>Parameter</th>
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<th>Prior</th>
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<td>1</td>
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<tr>
<td>Norm NC</td>
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<tr>
<td>$\nu / \bar{\nu}$</td>
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<td>fix</td>
<td>fix</td>
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* Only used for CP fits, not for NMH
Simulated measurement of $\delta_{CP}$

- Protvino to ORCA
  - $\delta_{CP}=0^\circ$
  - $\delta_{CP}=90^\circ$
  - $\delta_{CP}=180^\circ$
  - $\delta_{CP}=270^\circ$

NH neutrino beam
12 $\cdot$ 10$^{20}$ POT
ORCA layout
Construction status: sea infrastructure

Main electro-optical cable deployed
December 2014

Node1 (Junction Box) deployed
April 2015
Shown is deployment of an ARCA DU (ORCA similar)

First ORCA DU deployed in September 2017

Watch:
https://youtu.be/7HKHW0hLxt4
https://youtu.be/g2Y0KD3kdXs
https://youtu.be/xTj4ILMv1Fw
https://youtu.be/XFPCfCoTfUg
Calibration procedures

- Calibration procedures for KM3NeT
- Cross-calibration with muons
- Scattered photons, direct photons, nanobeacon
- Up to 150 Cherenkov $\gamma$ per decay; stable $^{40}\text{K}$ concentration
- $^{40}\text{Ca}$ (beta decay)

Graphs showing:
- Time offset
- Efficiency
- Time spread
- 2-fold coincidence rate [Hz]

KM3NeT preliminary data

Cross-calibration with muons
Why mass hierarchy is important

- Prime discriminator for theory models
- Helps measuring the CP phase
- Absolute mass scale
- Nature (Dirac vs Majorana)
- Origin of neutrino mass and flavour
- Core-Collapse Supernovae Physics

Impact of direct mass ordering measurement

Prime discriminator for theory models
- Helps measuring the CP phase
- Absolute mass scale
- Nature (Dirac vs Majorana)
- Origin of neutrino mass and flavour
- Core-Collapse Supernovae Physics

Sensitivity of future experiments

Core-Collapse Supernovae Physics

Walter Winter Neutrino 2014
Mass hierarchy measurement technicalities

- Pick random values for oscillation parameters and other systematics
- Generate pseudo-experiments for NO, IO cases
- Find best-fit likelihoods $L_{\text{NO}}$, $L_{\text{IO}}$ for the NO, IO cases (maximising w.r.t. 9 free parameters)
- Calculate the log-likelihood ratio $\log \left( \frac{L_{\text{NO}}}{L_{\text{IO}}} \right)$