KM3NeT - ORCA: measuring the neutrino mass ordering in the Mediterranean

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Abstract. ORCA (Oscillations Research with Cosmics in the Abyss) is the low-energy branch of KM3NeT, the underwater Cherenkov neutrino detector in the Mediterranean. Its primary goal is to resolve the long-standing unsolved question of the neutrino mass ordering by measuring matter oscillation effects in atmospheric neutrinos. To be deployed at the French KM3NeT site, ORCA’s multi-PMT optical modules will exploit the excellent optical properties of deep seawater to reconstruct cascade and track events with a few GeV of energy. This contribution reviews the methods and technology, and discusses the current expected performances.

1. Introduction

Neutrino flavour eigenstates ($\nu_e$, $\nu_\mu$, $\nu_\tau$) can be written as a linear combination of neutrino mass eigenstates ($\nu_1$, $\nu_2$, $\nu_3$) though the so-called PMNS\(^1\) matrix which can be parameterized as the product of three rotation matrices (related to the mixing angles $\theta_{12}$, $\theta_{13}$ and $\theta_{23}$) and a diagonal matrix containing the complex CP phase $\delta$. Current oscillation experiments provide measurements of the mixing angles $\theta_{ij}$ and the absolute values of the squared-mass splittings $\Delta m_{ij}^2 = m_i^2 - m_j^2$ ($i,j = 1,2,3$). While the sign of $\Delta m_{23}^2$ is known to be positive thanks to matter effects in the Sun, that of $\Delta m_{21}^2$ remains unknown. Two scenarios are thus possible: the normal ordering (NO: $m_1 < m_2 < m_3$) and the inverted ordering (IO: $m_3 < m_1 < m_2$). The knowledge of the neutrino mass ordering (NMO) is critical to better understand the fundamental physics underlying the generation of masses in the leptonic sector. It will also be an asset for the precise measurement of $\delta$ which in turns relates to fundamental laws explaining the observed abundance of matter over anti-matter.

The recent measurement of the non-vanishing mixing angle $\theta_{13}$, has put forward the possibility to use atmospheric neutrinos to measure this NMO via matter effects in the Earth\(^1\). Indeed, due the presence of electrons in the Earth, electron neutrinos will undergo a coherent forward scattering affecting their propagation in a different way than for other neutrino species, resulting in a so-called resonant effect \(^2\). This can be described adding an energy dependent potential $A$ in the Hamiltonian, whose sign is opposite for neutrinos and antineutrinos. The resonant condition is then met when the mass splitting $\Delta m_{21}^2$ and the potential $A$ have opposite signs (typically at energies $E_\nu \sim 6$ GeV for neutrinos crossing the mantle). An experiment observing as many neutrinos as antineutrinos would in principle be insensitive to the NMO. Fortunately

\(^1\) Pontecorvo-Maki-Nakagawa-Sakata
The detection principle is the observation of the Cherenkov light emitted by secondary particles produced by the neutrino interactions in and around the detector. The detector is therefore a 3-dimensional array of photosensors arranged along quasi-vertical strings anchored on the sea bed. The most innovative feature of the KM3NeT design with respect to the ANTARES one relies on the use of small 3-inch PMTs instead of a large 8-inch PMT housed in the water resistant glass sphere. A total of 31 PMTs can be placed in the same sphere, providing an increased photodetection surface, directional information and photon counting. Coincidences of PMT hits in the same sphere can also be used to reject the uncorrelated optical background.

In the benchmark design adopted for Monte Carlo studies, each string comprises 18 such spheres with a vertical spacing of 6 meters. A masking procedure is used to study the performances of the detector for vertical inter-sphere distance ranging from 6m to 15m. The footprint of this benchmark ORCA detector is depicted in Fig. 1. Keeping constant the number of optical modules, the corresponding instrumented volumes range from 3.7 Mt (6m vertical spacing) to 9.25 Mt (15m vertical spacing). As described in the next section, the optimum vertical spacing for the sensitivity to the NMO (trade-off between resolutions and effective mass), was found to be 9m, corresponding to an instrumented volume of 5.55 Mt.

3. Detector expected performances

The flavor oscillation patterns of GeV atmospheric neutrinos will be examined in the final energy and angular distributions of neutrinos of different flavors observed at the detector. Two distinct topologies are considered: tracks and cascades. Cascades are generated by hadronic interactions in the energy of interest, neutrinos and antineutrinos interaction cross-sections typically differ by a factor $\sim 2$, thus preserving some sensitivity. Following the successful operation of the first deep-sea neutrino telescope ANTARES that performed the first measurement of the oscillations parameters (with a threshold energy around 20 GeV) with an instrument of that kind, the KM3NeT collaboration has decided to devote its French site to the measurement of the NMO, with a detector dubbed ORCA.

2. The KM3NeT/ORCA design and technology

KM3NeT is a distributed research infrastructure with a network of deep-sea neutrino telescopes in the Mediterranean Sea. Two main physics goals are driving the project: the discovery and subsequent observation of high-energy neutrino sources in the Universe (ARCA) and the determination of the NMO (ORCA). While the ARCA component will be installed offshore Sicily, the ORCA site is located $\sim 10$km west from the ANTARES one, off the French Riviera. The same technology is used to implement both detectors.

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Figure 2. Left: median neutrino directional (3D) resolution as a function of neutrino energy for different upgoing shower-like neutrino event types. Right: relative energy resolution RMS/E as a function of the energy for electron neutrinos.

or electromagnetic showers developing inside the detector. They are therefore induced by $\nu_e$ charged current (CC) interactions and neutral current (NC) interactions of neutrinos of any flavor, as well as hadronic tau decays. Whenever a track can be fitted in addition to the observed shower, the topology can be referred to as track-like. This generally occurs for $\nu_\mu$ CC interactions, as well as for $\nu_e$ CC interactions when the tau decays into a muonic channel.

3.1. Track and Shower Reconstructions

Two separate algorithms have been developed for the reconstruction of tracks and cascades. The track reconstruction is adapted from ANTARES [7] and focuses on the muon direction. The neutrino energy estimation is mainly based on the reconstructed muon track length, with additional information from the number of hit PMTs. The time residuals under a spherical emission profile (cascade-like) or according to a Cherenkov cone are used to infer the inelasticity of the interaction.

The cascade reconstruction uses the long scattering length in sea water which preserves the structure of the Cherenkov light cone, to identify the leading lepton in the event. The interaction vertex is first identified with a resolution of about 0.5-1 m based on hit time residuals in a spherical fit ("bright point"). The direction, energy and inelasticity of the event are then obtained from a maximum likelihood fit based of Monte Carlo probability density functions. The reconstruction performance is shown in Fig. 2 for the cascade channel which contributes the most to the sensitivity to the NMO. The reconstructed inelasticity, though not very accurate, could be used for potential statistical separation between neutrinos and antineutrinos which in turn can further increase the sensitivity to the NMO, as suggested in ref [8].

3.2. Background rejection and particle identification

Atmospheric muons created in air showers and penetrating down to the detector are the most important source of background. The rejection strategy relies on the quality and accuracy of the reconstruction and on topological cuts. Indeed, in the relevant energy range, the reconstruction finds the vertex out of the instrumented volume for muons sneaking into the detector, while the vertices of neutrino events are found inside the instrumented volume. Using a multivariate technique based on several input seeds, a clean separation of these event samples is therefore achievable, reducing the background contamination to a tunable few percent without strong signal loss.

The same technique can be used to discriminate "shower-like" events from "track-like" events.
The plots illustrate that a $3\sigma$ significance can be obtained with 50% statistical power.

**Table 1.** Default parameter settings used for the study. The symbols $\mu$ and $\sigma$ refer to Gaussian distributions. The $\dagger$ indicates that the initial values for $\theta_{23}$ are generated in a special way as seven initial values are tried: $x + i \times 5^\circ$, with $x$ randomly drawn and $i \in [-3, -2, \ldots, 3]$. Two parameters ($\theta_{12}$ and $\Delta m^2_2$) are treated as nuisance parameters: a random "best fit" value is chosen and the parameter is not fitted. $\Delta M^2$ denotes $\Delta m^2_2 + \Delta m^2_3$.

| parameter | true value distr. | initial value distr. | treatment | prior |
|-----------|-------------------|----------------------|-----------|-------|
| $\theta_{23}$ [$^\circ$] | $\{40, 42, \ldots, 50\}$ | uniform over $[35, 55]$ | fitted | no |
| $\theta_{13}$ [$^\circ$] | 8.42 | $\mu = 8.42, \sigma = 0.26$ | fitted | yes |
| $\theta_{12}$ [$^\circ$] | 34 | $\mu = 34, \sigma = 1$ | nuisance | N/A |
| $\Delta M^2_1$ [$10^{-3} \text{eV}^2$] | $\mu = 2.4, \sigma = 0.05$ | fitted | no |
| $\Delta m^2_3$ [$10^{-5} \text{eV}^2$] | 7.6 | $\mu = 7.6, \sigma = 0.2$ | nuisance | N/A |
| $\delta_{CP}$ [$^\circ$] | 0 | uniform over $[0, 360]$ | fitted | no |
| overall flux factor | 1 | $\mu = 1, \sigma = 0.1$ | fitted | yes |
| NC scaling | 1 | $\mu = 1, \sigma = 0.05$ | fitted | yes |
| $\nu/\bar{\nu}$ skew | 0 | $\mu = 0, \sigma = 0.03$ | fitted | yes |
| $\mu/e$ skew | 0 | $\mu = 0, \sigma = 0.05$ | fitted | yes |
| energy slope | 0 | $\mu = 0, \sigma = 0.05$ | fitted | yes |

Table 1 indicates the parameters which are fitted, as well as the starting values for the fit. Besides the oscillation parameters whose uncertainties have the most important impact on the sensitivity to the NMO, 5 additional systematics are considered and listed as the 5 last rows of the table. Those essentially encompass the uncertainties on the normalization of the atmospheric fluxes and interaction cross sections, their energy dependence, and the confusion between atmospheric flavor and polarity composition.

The main one relies on likelihood ratios evaluated from a large number of pseudo-experiments (PE). Many parameters are fitted at the same time to account for the main uncertainties. The procedure is divided into several parts. First, the detector is modeled via response matrices and resolution functions based on the simulations described above. This allows calculating the expected event rates for given values of the oscillation parameters. Then, a statistical method for the NMO sensitivity is applied with the following main steps: a set of true values for the oscillation parameters and other systematics is chosen and pseudo-data are generated including Poisson fluctuations. Two histograms, one for tracks, one for showers, then constitute one PE. These are fitted under NO and IO assumptions, by maximizing the likelihood with respect to the other free parameters. The log-likelihood ratio of the 2 hypotheses is finally used as a discriminating variable.

A Random Decision Forest is trained with full Monte Carlo samples. The ranking of the decision tree is done under a majority of 50% at each step. The iteration process continues as long as the overall performance increases. As a result, showering events wrongly identified as track fall below a fraction of 20% above 10 GeV. Electron neutrinos are identified more easily as shower-like than neutral current reactions as they yield more light. Above 15 GeV the fraction of correctly classified electron neutrino charged current interactions surpasses 90%, while at 6 GeV this fraction already achieves 85%. Charged current muon neutrino events are falsely classified at a rate of 10% to 20% depending on the neutrino energy.

### 4. Sensitivity to the Neutrino Mass Ordering and Oscillation Parameters

Several algorithms to evaluate the sensitivity of ORCA to the NMO have been developed. The main one relies on likelihood ratios evaluated from a large number of pseudo-experiments (PE). Many parameters are fitted at the same time to account for the main uncertainties. The procedure is divided into several parts. First, the detector is modeled via response matrices and resolution functions based on the simulations described above. This allows calculating the expected event rates for given values of the oscillation parameters. Then, a statistical method for the NMO sensitivity is applied with the following main steps: a set of true values for the oscillation parameters and other systematics is chosen and pseudo-data are generated including Poisson fluctuations. Two histograms, one for tracks, one for showers, then constitute one PE. These are fitted under NO and IO assumptions, by maximizing the likelihood with respect to the other free parameters. The log-likelihood ratio of the 2 hypotheses is finally used as a discriminating variable.
after 3 years of data taking, the worst case scenario. In the NO case and if $\theta_{23}$ is as large as $48^\circ$, 5\sigma significance could be obtained after 1.5 years of data taking.

The sensitivity to other oscillation parameters such as $\theta_{23}$ and $\Delta M^2$ is also derived incorporating the same systematics (plus an additional energy scale factor), but currently with a simplified procedure, which has been tested to provide similar results for the NMO. After 3 years of data taking, ORCA is expected to provide significantly better sensitivity to $\theta_{23}$ and $\Delta M^2$ with respect to the current knowledge and the projected values of running experiments [9]. Preliminary estimates indicate that a 1\sigma precision of $\sim 3\%$ is expected on $\Delta M^2$ and that 4%-10% could be achieved, depending on the true value of $\sin^2 \theta_{23}$.

5. Conclusions
The successful exploitation of the ANTARES detector validates the concept of deep-sea neutrino observatories and the expected performances of the next generation detector KM3NeT. The low-energy branch of KM3NeT -ORCA- will comprise 115 detection strings with 20m horizontal (9m vertical) spacing. Such configuration provides a detection threshold down to a few GeV, thus permitting the study of subdominant effects in the neutrino flavor conversion. The performances of the detector have been assessed with full Monte Carlo simulations and incorporating the main identified sources of systematics. The latest results indicate that the NMO can be unraveled with at least 3 \sigma significance after 3 years of data taking. Funding permitting, this could be achieved as early as 2023.

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