Measuring the neutrino mass hierarchy with KM3NeT/ORCA

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Abstract. ORCA is the low-energy branch of KM3NeT, the next-generation research infrastructure hosting underwater Cherenkov detectors in the Mediterranean Sea. ORCA’s primary goal is the determination of the neutrino mass hierarchy by measuring the matter-induced modifications on the oscillation probabilities of few-GeV atmospheric neutrinos. The technical design of the ORCA detector foresees a dense configuration of optical modules, optimised for the study of interactions of neutrinos in the energy range of 3–30 GeV. The first ORCA detection string was successfully deployed on 22nd September 2017 and is providing high-quality data since then.

With an instrumented mass of 8 Mton for the full-size ORCA detector, it will be possible to probe with a high-statistics neutrino sample a wide range of energies and baselines through the Earth. This allows to determine the neutrino mass hierarchy with 3σ after 3–4 years of operation, to probe the unitarity assumption of 3-neutrino mixing with a high-statistics measurement of tau-neutrino appearance in the atmospheric neutrino flux, and to improve the measurement precision on other oscillation parameters.

1. Introduction

The KM3NeT collaboration has started to construct two next-generation underwater neutrino telescopes in the Mediterranean Sea, named ARCA and ORCA. The two detectors share the same technology while targeting different neutrino energy regimes and physics goals. While ARCA (Astroparticle Research with Cosmics in the Abyss) is a sparse gigaton-scale detector optimised for TeV–PeV neutrino astronomy [1], ORCA (Oscillation Research with Cosmics in the Abyss) is a dense megaton-scale detector optimised for measuring the oscillation of few-GeV atmospheric neutrinos in order to determine the neutrino mass hierarchy.

In the standard 3-neutrino scheme, the mixing matrix relating the neutrino flavour eigenstates ($\nu_e$, $\nu_\mu$, $\nu_\tau$) to the mass eigenstates ($\nu_1$, $\nu_2$, $\nu_3$) is parameterised in terms of three mixing angles $\theta_{12}$, $\theta_{13}$ and $\theta_{23}$, and a CP-violating phase $\delta_{CP}$. Oscillation experiments are mostly sensitive to mass-squared differences $\Delta m^2_{ij} = m^2_i - m^2_j$ ($i,j = 1,2,3$). Global fits of available data form a coherent picture and provide the oscillation parameters values with reasonable precision [2], but several fundamental properties remain to be determined: the value of $\delta_{CP}$, the octant of $\theta_{23}$ (i.e. whether $\theta_{23}$ is greater or smaller than $\pi/4$) and the so-called neutrino mass hierarchy (NMH). The latter refers to the ordering of the neutrino mass eigenstates, which is either $m_1 < m_2 < m_3$ (normal hierarchy, NH) or $m_3 < m_1 < m_2$ (inverted hierarchy, IH).
The strategy followed by ORCA and other next-generation experiments to determine the NMH is to measure the energy and zenith-angle dependent oscillation pattern of few-GeV atmospheric neutrinos that have traversed the Earth towards the detector. Due to matter-induced modifications [3] on the oscillation probabilities in conjunction with different interaction cross-sections and atmospheric fluxes for neutrinos and antineutrinos, the expected event rates in the energy regime of 3–30 GeV are different for NH and IH [4]. With the same data, ORCA can perform also a high-statistics measurement of tau-neutrino appearance in the atmospheric neutrino flux, which allows to probe deviations from the unitarity assumption of the 3-neutrino mixing.

A first estimation of the sensitivity of ORCA to the NMH as well as other oscillation parameters has been published in the ‘Letter of Intent for KM3NeT 2.0’ (LoI) [5]. Since then the detector geometry has been updated and significant improvements in event triggering and reconstruction have been made. The detector design assumed in the LoI and the updated detector geometry are described in Sec. 2. In Sec. 3, the performance of the LoI detector is summarised and the recent improvements are discussed. Simulations for the new detector configuration are still ongoing, therefore the results achieved with the detector studied in the LoI, in terms of NMH sensitivity, measurement precision on $\theta_{23}$ and $\Delta m^{2}_{32}$ and sensitivity to tau-neutrino appearance, are described in Sec. 4. Finally, the current status of the ORCA detector construction, including the deployment of the first detection string, is discussed in Sec. 5.

2. The KM3NeT/ORCA detector
The ORCA detector design foresees a 3-dimensional array of photosensors that register the Cherenkov light produced by charged particles emerging from neutrino-induced interactions. From the arrival time of the Cherenkov photons (nanosecond precision) and the position of the sensors (≈10 cm precision), the energy and direction of the incoming neutrino, as well as other parameters of the neutrino interaction, can be reconstructed.

A key KM3NeT technology is the Digital Optical Module (DOM), a pressure-resistant glass sphere housing 31 small 3-inch PMTs, their associated electronics and calibration devices. The DOMs are arranged in strings held vertical by a submarine buoy and anchored to the seabed. Each string comprises 18 DOMs. The strings are connected to junction boxes that provide connections for power and data transmission. The full-size ORCA detector will comprise 115 such strings. The ORCA detector site is 40 km offshore Toulon, in a depth of about 2450 m.

In the LoI [5], a detector design with a vertical spacing of about 9 m between the DOMs and an average horizontal spacing between neighbouring strings of roughly 20 m is assumed. The instrumented mass is about 5.7 Mton of seawater. This detector configuration was found to provide the best NMH sensitivity with the detector performance assumed in the LoI.

In the updated detector design, several technical constraints from the deployment procedure are taken into account. The vertical inter-DOM spacing varies between 8.7 m and 10.9 m (9.3 m average) and the average horizontal inter-string spacing is increased to about 23 m. The new detector configuration has a instrumented mass of about 8 Mton and is about 1.4 times larger in volume than the detector studied in the LoI, with the same number of DOMs. The detector performance degradation due to the smaller instrumentation density has been counterbalanced by improvements in the event triggering and reconstruction.

3. Expected detector performance
The expected detector performance has been determined based on detailed simulations of the neutrino interaction, particle propagation and Cherenkov photon generation, tracking in seawater as well as detection. Optical background from $^{40}$K decays in the seawater as well as the background from downgoing atmospheric muons is taken into account. Further details are given in the LoI [5].
Two distinct event topologies are observed by the detector: track-like event topologies are induced by $\nu_\mu$ charged-current (CC) interactions, while $\bar{\nu}_e$ CC and $\bar{\nu}_{e,\mu,\tau}$ neutral-current (NC) interactions induce shower-like event topologies. Depending on the tau-decay channel, $\nu_\tau$ CC interactions can appear as track-like or shower-like. Dedicated event triggering and reconstruction strategies for track-like and shower-like events, as well as an event topology classification algorithm, have been developed and are described in the LoI [5].

Compared to the detector performance achieved in the LoI, significant improvements have been made in the event triggering and reconstruction of faint events with only a few tens of detected photons. Most importantly, a new trigger algorithm has been developed for ORCA, which not only includes causally-connected L1 hits (coincidentally recorded photons on two PMTs of the same DOM) but is based on single hits (L0 hits) in the vicinity of a L1 hit. All hits have to be causally connected among each other. This new trigger significantly increases the effective volume in the few-GeV energy range, while still satisfying the bandwidth requirements of the data acquisition system, i.e. the trigger rate due to pure noise is smaller than the irreducible trigger rate due to atmospheric muons of about 50 Hz.

As shown in Fig. 1 (left), the effective volume is as large as the instrumented volume of the detector, being reached for $\bar{\nu}_{e,\mu}$ CC with $E_\nu > 10$ GeV, while 50% efficient at about 4 GeV (5 GeV) for the new detector configuration (detector studied in LoI). The 20% faster turn-on is a consequence of the improvements in event triggering and reconstruction, while the 40% larger plateau value is due to the larger instrumented volume. With these improvements, the new detector configuration will provide data samples of about 90000 upgoing neutrinos per year, which is roughly 70% more than in the LoI [5].

Fig. 1 (right) shows the median neutrino zenith-angle resolution. The resolution is better than $5^\circ$ for $\bar{\nu}_{e,\mu}$ CC events with $E_\nu \geq 10$ GeV. Direction reconstruction improvements of up to $\sim 1^\circ$ with respect to the detector performance in the LoI are achieved for $E_\nu \geq 10$ GeV. The energy resolution is Gaussian-like with $\sigma_{E_\nu}/E_\nu \approx 25\%$ for $E_\nu = 10$ GeV. Due to the more efficient trigger and reconstruction for low-energy events, fainter events are detected, resulting in a slightly deteriorated energy resolution, which is still dominated by intrinsic light yield fluctuations in the hadronic shower [6].

**Figure 1.** Effective volume (left) and median neutrino zenith-angle resolution (right) for $\bar{\nu}_e$ CC events shown for the new (red) and the detector configuration studied in the LoI [5] (black), with and without the latest improvements in event triggering and reconstruction. Similar performances are achieved for $\bar{\nu}_\mu$ CC events, as shown in [10].
4. Sensitivity to neutrino mass hierarchy and tau-neutrino appearance

As the simulation of the updated detector configuration with the improvements in event triggering and reconstruction is still ongoing, the results summarized in the following are based on the detector performance achieved in the LoI [5]. However, it is expected that the significantly increased effective detector volume (cf. Fig. 1 left) will result in improved sensitivities.

The sensitivity to the mass hierarchy is calculated using log-likelihood ratio distributions from pseudo-experiments. Systematic uncertainties from neutrino fluxes, interaction cross-sections as well as the detector response (overall normalization, energy slope, $\nu/\bar{\nu}$ skew, $\mu/e$ skew and NC/CC skew), and current uncertainties on oscillation parameters ($|\Delta m^2_{31}|$, $\theta_{23}$, $\theta_{13}$, and $\delta_{\text{CP}}$) are incorporated as nuisance parameters. Figure 2 (left) shows the median significance of ORCA to exclude the wrong hierarchy hypothesis after 3 years of data taking as a function of the true value of $\theta_{23}$ and assuming no CP-violation, i.e. $\delta_{\text{CP}}$ equals 0 or $\pi$. The NMH can be determined with about 3 $\sigma$ after 3 years of operation for the experimentally allowed range of $\theta_{23}$ and assuming $\delta_{\text{CP}} = 0$. ORCA is moderately sensitive to the CP-phase and the significance is reduced by at most 0.5 $\sigma$ if $\delta_{\text{CP}} = \pi$ is realised in nature. In case of NH and $\theta_{23} > \pi/4$, the sensitivity increases dramatically and the significance after 3 years of operation can reach up to 7 $\sigma$.

ORCA can also improve the measurement precision on $|\Delta m^2_{32}|$ and $\theta_{23}$, and in particular, determine the octant of $\theta_{23}$ for a wide range of the allowed parameter range. With 3 years of operation, a precision of about 3% in $|\Delta m^2_{32}|$ and 5% (12%) in case of NH (IH) can be achieved [5]. This is comparable with the predicted sensitivity of NO$\nu$A [7] and T2K [8] in 2020, and can be obtained with different systematics than the accelerator-based experiments.

With about 3000 detected $\bar{\nu}_\tau$ events per year, ORCA can also measure the $\bar{\nu}_\tau$ flux normalisation from $\bar{\nu}_\mu \to \bar{\nu}_\tau$ conversion in the energy region of $E_\nu \approx 25$ GeV. The measurement uncertainty on the $\bar{\nu}_\tau$ flux normalisation as a function of operation time is shown in Fig. 2 (right). After one year of operation, the $\bar{\nu}_\tau$ appearance rate will be constrained to better than 10% precision, assuming unitarity of 3-neutrino mixing. Further details are given in [9].

Additional science topics of ORCA include: indirect searches for sterile neutrinos [10], non-standard interactions [10], dark matter [11] and other exotic physics; neutrino oscillation tomography of the Earth’s interior [12]; and low-energy neutrino astrophysics [13, 14]. The

Figure 2. Left: median NMH significance to exclude the other hierarchy hypothesis assuming true NH (red), IH (blue), $\delta_{\text{CP}} = 0$ (solid) or $\delta_{\text{CP}} = \pi$ (dashed) as a function of true $\theta_{23}$. Three years of data taking with the full-size ORCA detector are assumed. Right: sensitivity to $\bar{\nu}_\tau$ appearance as a function of operation time of the full-size ORCA detector. A normalisation of one is expected in case of unitary 3-neutrino mixing. Figures taken from [5] and [9], respectively.
KM3NeT research infrastructure will also house instrumentation for Earth and Sea sciences, such as marine biology, oceanography and geophysics.

Possible future options could be a long-baseline neutrino beam targeted to ORCA [15], and a significantly denser detector instrumentation lowering the detection threshold to measure the CP-phase $\delta_{CP}$ with atmospheric neutrinos [16].

5. Status of the ORCA detector construction

The first string of the ORCA detector was successfully deployed on 22nd September 2017 during an extensive sea operation. The detection string, wound around its spherical launching frame (see left picture on the right), was carefully lowered to the seafloor within two metres of its designated position. Since its deployment, it is sending high-quality data from more than 550 PMTs ($18 \times 31$). An event display of one of the first downgoing atmospheric muon events is shown on the right. The colour coding illustrates the arrival time of the light, ranging from yellow (early hits) to turquoise to magenta (later hits), and the funnels illustrate the PMT orientations. An animation of this event and a video of the sea operation can be found in [17].

The main electro-optical cable (Dec. 2014) and junction box (Oct. 2016) were already deployed earlier. An array comprising 7 detection strings is funded and expected to be completed and operational in 2018. It will demonstrate the feasibility of the measurement and to validate and optimise the detector design. The full-size ORCA detector comprising 115 detection strings could be deployed within 3 years.

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