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ORCA: measuring the neutrino mass hierarchy with an underwater Cherenkov detector

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Abstract

It has recently been suggested that the neutrino mass hierarchy can be determined from the oscillation pattern of atmospheric neutrinos passing through the Earth in the energy regime of about 3–20 GeV. In this paper we present the status of a feasibility study for ‘Oscillation Research with Cosmics in the Abyss’ (ORCA) to evaluate the potential of a megaton-scale underwater Cherenkov detector to determine the mass hierarchy employing the deep-sea neutrino telescope technology developed for the KM3NeT project.

Keywords: Neutrino Mass Hierarchy, Atmospheric Neutrinos, Neutrino Telescopes, Neutrino Oscillations

1. Introduction

Recent measurements by several short-baseline reactor experiments [1, 2, 3] have shown that the value of the third neutrino mixing angle θ_{13} is non-zero. The relatively large value of this parameter, $\sin \theta_{13}$ close to 0.1, provides the opportunity to determine the ordering of the neutrino mass eigenstates, also known as the neutrino mass hierarchy (NMH). While the absolute mass-squared differences of the three eigenstates are precisely known, it is still unclear whether the third mass eigenstate lies above (normal hierarchy, NH) or below (inverted hierarchy, IH) the first and the second eigenstate. The latter are closely spaced and their ordering is known from solar neutrino physics.

Recently, it has been suggested that underwater (-ice) neutrino detectors with a relatively modest volume might be able to provide significant sensitivity to the NMH by using the flux of atmospheric neutrinos that have passed the Earth towards the detector [4]. Due to matter-induced oscillation effects in the Earth in conjunction with different cross-sections and atmospheric

neutrino fluxes for neutrinos and antineutrinos, the expected event rates of neutrinos in the energy regime of about 3–20 GeV are different for NH and IH. Therefore, depending on the experimental resolutions of neutrino energy and zenith angle – the latter defining the neutrino path length through the Earth – a determination of the NMH is possible.

In the following we present the status of a feasibility study for ‘Oscillation Research with Cosmics in the Abyss’ (ORCA) to evaluate the potential of a megaton-scale underwater Cherenkov detector in the Mediterranean Sea to determine the NMH¹.

2. Detector

The ORCA detector defined for the feasibility study presented here uses the technology developed for KM3NeT, the future multi-km³ water Cherenkov neutrino telescope in the Mediterranean Sea, which is currently under construction [7]. The detection principle is that of a 3-dimensional array of photo-sensors that register the Cherenkov light induced by charged particles

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¹A similar study is also pursued within the IceCube collaboration: *Precision IceCube Next-Generation Upgrade, PINGU* [5, 6].

produced in a neutrino-induced interaction. From the arrival time of the Cherenkov photons (nanosecond precision) and the position of the sensors (uncertainty about 10 cm), the energy and direction of the incoming neutrino can be reconstructed. Key elements of the detector are pressure-resistant optical modules (OMs), equipped with photomultipliers (PMTs), suspended from string-like structures held vertically by a buoy and anchored to the seabed. Each OM contains 31 3-inch PMTs, 19 in the lower and 12 in the upper hemisphere [8].

The KM3NeT detector is optimised for the measurement of astrophysical neutrinos in the TeV–PeV energy range. For the ORCA study the distances between the OMs are reduced in order to obtain sensitivity to the detection of neutrinos at the energies needed for the measurement.

For this study, a ‘reference detector’ was chosen with 1000 OMs distributed over 50 strings placed in a semi-random pattern in a circular footprint. In this design, each string hosts 20 OMs with a 6 m vertical spacing. The mean horizontal distance between adjacent strings is roughly 20 m. The instrumented volume is $1.75 \times 10^6 \text{ m}^3$, corresponding to about 1.8 Mton of sea water.

The collaboration has recently proposed to build a detector of 115 strings with 18 OMs each (see Figure 1). For the same spacing as that of the reference detector this corresponds to an instrumented volume of $3.65 \times 10^6 \text{ m}^3$. This proposed detector could be built in 4 years, with an investment budget of 40 M€ [9]. Note that simulations performed for the 50-string reference detector have been used in this study, suitably extrapolated to the detector configuration investigated.

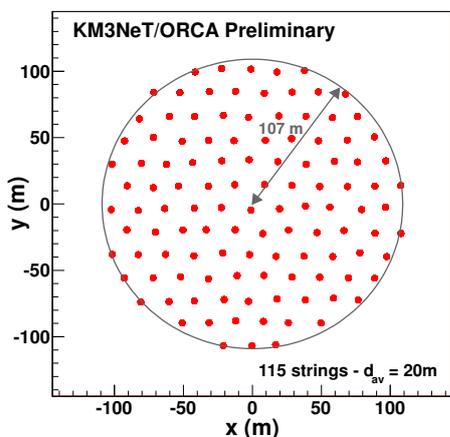


Figure 1: Footprint of the proposed 115-string detector.

3. Expected Performances

The key parameters for the determination of the NMH are the effective mass of the detector and the experimental resolutions for the zenith angle θ_ν and energy E_ν of the incoming neutrino. Detailed Monte-Carlo (MC) simulations of the reference detector have been performed using GENIE [10] for simulation of neutrino interactions and simulation packages developed and used by the ANTARES [11] collaboration as well as the KM3NeT collaboration [12] for the particle propagation and Cherenkov photon generation. Optical background from ^{40}K decays has been taken into account.

Two distinct event topologies can be considered: tracks and showers. Showers are initiated by hadronic or electromagnetic particles produced as the result of the neutrino interaction. They are induced by $\bar{\nu}_e$ charged current (CC) interactions and neutral current (NC) interactions of (anti-)neutrinos of all flavours. Muons with a velocity above the Cherenkov threshold produce track-like signatures in the detector. Therefore, track-like events are induced by $\bar{\nu}_\mu$ CC interactions, as well as $\bar{\nu}_\tau$ CC interactions with muonic tau decays. In these events the muon is accompanied by a hadronic shower. The reconstruction strategies, both for tracks and showers, are adapted from ANTARES and not yet fully optimised. For the track reconstruction a likelihood maximisation using the hit time residuals is performed and the muon energy is estimated from the reconstructed track length. The method is described in detail in [13]. Energy and direction resolutions have been evaluated on up-going $\bar{\nu}_\mu$ CC and are discussed e.g. in [14]. A median zenith resolution better than 10° for $E_\nu \geq 5 \text{ GeV}$ is achieved. Using the reconstructed muon energy as a neutrino energy estimator, a median energy resolution of 35% can be reached at 10 GeV. Studies are ongoing to evaluate the energy deposited in the hadronic shower in order to improve the neutrino energy determination.

For the shower vertex and direction reconstruction a likelihood maximisation based on hit probabilities is performed and the energy is estimated from counting the number of OMs which have at least one selected signal-like hit. Energy and direction resolutions have been evaluated on up-going $\bar{\nu}_e$ CC events, for which most of the Cherenkov light is contained in the instrumented volume (selected using MC information). Under these optimistic assumptions, the median zenith is better than 10° and the energy resolution better than 30% for $E_\nu \geq 5 \text{ GeV}$. However, recent results indicate that a novel shower reconstruction, which simultaneously also fits the inelasticity of the neutrino interaction, can achieve similar resolutions, while having a

sufficiently high event selection efficiency.

For the definition of track- and shower-like event samples, the events are classified using a random decision forest based on several features calculated on a track and shower hypothesis. The identification (in)efficiencies have been evaluated on nearly fully contained events and are included in the presented study. Under these optimistic conditions, we find the probability to misidentify a shower as a track to be below 20% in the full energy range and the probability to misidentify a track as a shower to decrease with energy, being below 20% for $E_\nu \geq 5$ GeV.

The main source of background are atmospheric muons penetrating to the detector and reconstructed as up-going. The rejection of these events seems well within reach applying cuts on the reconstruction quality and on the reconstructed vertex position. A separation between $\vec{\nu}_\mu$ CC and penetrating atmospheric muon events is possible with a background contamination of 10% or even as low as 1% without a prohibitive loss of signal events [14].

Building on the expected performance, a significance analysis is performed by generating a large number of ‘pseudo-experiments’ (PEs) simulating measurements of event distributions in the reconstructed (E_ν, θ_ν) plane. Each PE is generated by assuming a true hierarchy and a set of oscillation parameters. Then, each PE is analysed by performing a log-likelihood fit with the oscillation parameters as free parameters and assuming either NH or IH. The likelihood ratio resulting from these fits is used to quantify the separability of the two hierarchies. The results indicate that ORCA can significantly constrain Δm_{23}^2 and θ_{23} beyond their current precision but is rather insensitive to the other oscillation parameters [14]. The sensitivity to the NMH determination is shown in Figure 2 for the proposed 115-string detector. Note, however, that for the presented sensitivity several ingredients are missing, like the neutrino flux and cross-section uncertainties as well as NC and $\vec{\nu}_\tau$ CC events, realistic resolutions for misidentified events and an atmospheric muon background contamination. Under these assumptions, we find that a 3σ median significance after 2 years of data taking with the proposed detector, corresponding to roughly 7.5 Mton \times years, seems feasible. An important fraction of the overall sensitivity arises from the electron channel. We expect a significant improvement for the track channel, once the hadronic shower is incorporated in the reconstruction.

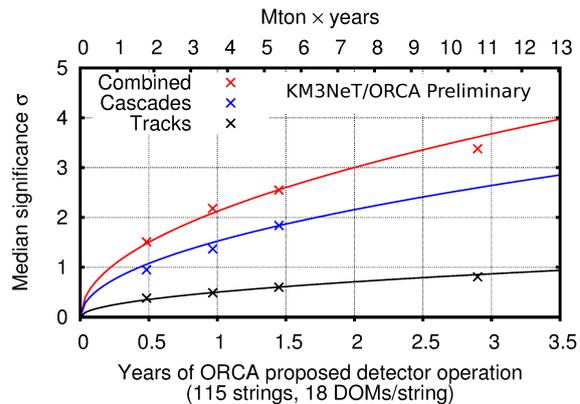


Figure 2: Median significance as a function of lifetime for the proposed 115-string detector, cf. Section 2. The colored markers represent the estimated significance for a given exposure, while the lines show the expectation from a $\sqrt{\text{time}}$ dependence. The black and blue lines show the sensitivity in the track and shower channel separately. The red line is the combined sensitivity arising from both channels together. Here, only the first octant of θ_{23} is considered. For the second octant larger significances are achieved.

4. Conclusions and Outlook

We have investigated the feasibility of determining the neutrino mass hierarchy using the deep-sea neutrino telescope technology developed for KM3NeT. We find that a 3σ significance after 2 years of data taking with the proposed 115-string detector is in reach, however, neglecting some systematics and using optimistic assumptions. Further investigation into different detector configurations and optimisation of the reconstruction methods is under way.

A possible future option could be a long-baseline neutrino beam targeted on ORCA, as discussed in [15].

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