ORCA: measuring the neutrino mass hierarchy with atmospheric neutrinos in the Mediterranean

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Abstract. Since the measurement of the mixing angle $\theta_{13}$, the determination of the neutrino mass hierarchy has become a central challenge of neutrino physics. Recent studies have pointed out that it could reveal itself in the atmospheric neutrino sector, where oscillations are affected by Earth matter effects. This contribution reports on the ORCA feasibility study for such a measurement with an underwater Cherenkov detector based on the technology developed for the KM3NeT neutrino telescope. The baseline performances are discussed for a reference detector with 50 instrumented lines. Preliminary projections, based on the muon channel only, indicate that a $3 - 5 \sigma$ significance measurement is within reach of a detector with an exposure of the order of 20 Mton years. Further improvement is expected to come from the electron channel, which is currently under study.

1. Introduction and motivations

In the past decade, a large variety of experiments have provided compelling evidence for neutrino oscillations, implying the existence of non-zero neutrino masses. The values of all mixing angles and squared-mass differences in the standard, $3\nu$, oscillation scheme are by now extracted from global fits of available data with a reasonable precision [1, 2, 3]. The recent measurements of a relatively large value for the mixing angle $\theta_{13}$, which drives the $\nu_\mu \leftrightarrow \nu_e$ transition amplitude, is an asset for the subsequent searches for the remaining unknowns in the neutrino sector, and in particular for the determination of the neutrino mass hierarchy (NMH, normal: $m_1 < m_2 < m_3$ or inverted: $m_3 < m_1 < m_2$). This question is of fundamental importance to constrain the theoretical models that seek to explain the origin of mass; it also impacts the performances of next-generation experiments looking for a leptonic CP-violating phase $\delta$, the absolute value of the neutrino masses, and their Dirac or Majorana nature.

A high-significance ($\geq 5 \sigma$) NMH determination remains challenging and could take as long as 15 to 20 years even within optimistic estimates [4, 5, 6]. The reach of neutrino beam experiments depends on the still unknown value of $\delta_{CP}$, while atmospheric neutrino experiments suffer from the larger systematics uncertainties and relatively low statistics. The latter probe $\sim 1 - 100$ GeV $\nu_e \leftrightarrow \nu_\mu$ oscillations over a wide range of baselines and neutrino energies, accessing thereby the richness of matter effects that arise in the propagation of neutrinos through the Earth and that reflect in the energy vs. zenith angle oscillogram patterns (see e.g. collective references in [5]). In this context, megaton-scale underwater/ice detectors similar (but denser) to the existing neutrino telescopes and with an energy threshold around the GeV have been proposed as possible contenders for the NMH measurement [7, 8].
2. The ORCA feasibility study

ORCA (Oscillation Research with Cosmics in the Abyss) is a proposal to conduct a deep-sea water Cherenkov experiment dedicated to the NMH measurement with atmospheric neutrinos in the $1 - 100$ GeV range. The detector will be a dense array of multi-PMT digital optical modules (DOMs) [9] using technology developed for KM3NeT, the future multi-km$^3$ neutrino telescope in the Mediterranean Sea [10]. The DOMs are distributed along flexible strings anchored to the sea bottom and held up by a buoy; each of them is equipped with 31 3-inch photomultipliers. The final design of the detector may still depend on the outcome of a dedicated optimisation study which is currently being performed using an overdense detector with maskable DOMs.

The studies presented here have been conducted with a reference detector based on a realistic design in view of the technical and deployment constraints; its cost is estimated at $\sim 20$ M€. The total height and horizontal spacing of the lines are indeed limited by the deformation of the lines induced by sea currents, and the accuracy of the deployment on the sea bed is, from the ANTARES experience, about 5m [11]. The reference detector comprises 1000 optical modules (OM) distributed on 50 lines arranged in a semi-random pattern inside a circular footprint, with a typical interline spacing of 20m and an inter-OM spacing of 6m. It corresponds to an instrumented water mass of 1.8 Mton. Detailed Monte-Carlo simulations are being conducted to address the main performances of the detector: the trigger and event selection efficiencies, the energy and angular resolutions, the flavour identification capabilities (in particular $\nu_\mu$ vs. $\nu_e$), the strategies for background rejection and the impact of systematics effects [12].

Studies have so far concentrated on the muon channel, $\nu_\mu N \rightarrow \mu X$, with up-going neutrinos (i.e. zenith angle $\theta > 90^\circ$). The event reconstruction currently provides the muon track length and direction, the vertex position and a quality parameter $\Lambda$. Well-reconstructed events are selected by cutting on $\Lambda$ and requiring the reconstructed vertex to be inside the instrumented volume. The corresponding effective volume is shown in Fig. 1 (left panel) as a function of the simulated neutrino energy $E_\nu$. A median angular accuracy better than 15$^\circ$ (resp. 10$^\circ$) above 1 GeV (resp. 5 GeV) has been achieved for the muon neutrino; such a resolution is already mostly dominated by the intrinsic $\nu_\mu$ to $\mu$ angle, demonstrating the capabilities of water as a particle tracker medium. The interaction vertex can be reconstructed with an accuracy of a few meters, which is also an asset for muon background rejection. The energy estimate is currently based
on the reconstructed muon tracklength of (semi-)contained events; in the region below 10 GeV where most muon tracks are contained, the typical energy resolution is around $30\% \times E_\mu$. It is anticipated that this resolution will improve once the information from the associated cascade will be included in the reconstruction algorithm.

A likelihood ratio hypothesis test based on pseudo-experiments with a concomitant fit of the oscillation parameters is employed to compute the sensitivity of the experiment for the NMH measurement. Results are shown in Fig 1 (right panel) for different assumptions on the neutrino energy resolution; they can be taken as realistic but on the optimistic side, as the impact of background from atmospheric muons and from other neutrino reactions were neglected so far. A future improvement in the muon channel might still be possible by using the inelasticity parameter $y$ for $\nu/\bar{\nu}$ separation, as suggested in [13].

It has recently become evident that including the electron channel, $\nu_eN \rightarrow eX$, in the analysis can substantially contribute to the significance of the NMH measurement. Although the statistics for $\nu_e$-induced events is smaller, the difference between hierarchies in this channel and indeed largely energy-independent in the energy range of interest, and therefore more robust against detector-related systematics. A thorough study of this channel requires good $\nu_e-\bar{\nu}_e$ discrimination capabilities, and efficient reconstruction algorithms for cascade-like events. Preliminary studies on the cascade channel (from all neutrino flavors), including resolution effects on energy and zenith angle, contributions from neutral current interaction channels and $\nu_\tau$ events, indicate that this channel could provide a substantial improvement in sensitivity, as it is the case for the PINGU in-ice proposal [14]. The overall performance of ORCA is still under study.

3. Conclusions and outlook
ORCA has investigated the feasibility of determining the NMH in a densely instrumented water Cherenkov experiment using the technology of KM3NeT, by measuring the energy and zenith distribution of atmospheric neutrinos. Preliminary studies based on the muon channel alone have shown that a $3-5\sigma$ significance measurement could be within reach of a detector with an overall exposure of 20 Mton year. Including the cascade channel sensitive to $\nu_e$ is likely to further improve the prospects, turning ORCA into a competitive experiment in terms of cost and timescale. In addition, the possibility of a neutrino beam from Protvino to the ORCA site [15] should also be investigated further as it would be close to the magical baseline where the separation between normal and inverted hierarchies is optimal.

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