Contribution to IN2P3 Prospective GT06: Neutrino physics with KM3NeT/ORCA

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September 25, 2019

1 Introduction

The main objectives of the KM3NeT[1] experiment are *i)* the discovery and subsequent observation of high-energy neutrino sources in the Universe and *ii)* precisely measure atmospheric neutrino oscillations with particular focus on the determination of the mass hierarchy of neutrinos. To meet these objectives, the KM3NeT Collaboration is in the process of building a new research infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea. A phased and distributed implementation is pursued which maximises the access to regional funds, the availability of human resources and the synergetic opportunities for the earth and sea sciences community.

The KM3NeT infrastructure will consist of three so-called "building blocks". A building block comprises 115 detection strings, each string comprises 18 optical modules and each optical module comprises 31 photo-multiplier tubes. Each building block thus constitutes a 3-dimensional array of photo sensors that can be used to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions.

Two building blocks will be configured to fully explore the IceCube diffuse signal for cosmic neutrinos with different methodology, improved resolution and complementary field of view, including the Galactic plane. Collectively, these building blocks are referred to as ARCA (Astroparticle Research with Cosmics in the Abyss). ARCA will be realised at the Capo Passero site in Sicily, Italy.

One building block will be configured for low energy neutrinos (¿3 GeV). This building block is referred to as ORCA (Oscillation Research with Cosmics in the Abyss). ORCA will be realised at the Toulon site in Southern France. Due to KM3NeT's flexible design, the technical implementation of ARCA and ORCA is almost identical. The Letter of Intent for the Phase 2 of KM3NeT describes the physics opportunities and detector design [1].

The KM3NeT project is on the French roadmap of Research Infrastructures and is selected by the 2016 roadmap of the European Strategy Forum on Research Infrastructures (ESFRI). It is strongly supported by the APPEC roadmap.

In this document we focus on the neutrino physics opportunities of the KM3NeT/ORCA array. A separate contribution presents the neutrino multi-messenger astronomy aspects of KM3NeT [2].

2 neutrino studies with atmospheric neutrinos

In the standard 3-neutrino scheme, the PMNS mixing matrix, which relates the neutrino flavour eigenstates to the mass eigenstates (ν_1, ν_2, ν_3), can be parameterised in terms of 3 mixing angles θ_{12} θ_{13} θ_{23}, and a CP-violating phase δ. Oscillation experiments are not sensitive to the absolute value of neutrino masses but do provide measurements of the squared-mass splittings $\Delta m^2_{ij}(i, j = 1, 2, 3)$. The values of all these mixing parameters are now extracted from global fits of available data with a reasonable precision. Despite this tremendous progress, many fundamental properties of the neutrino have yet to be determined: the octant

[1] http://www.km3net.org

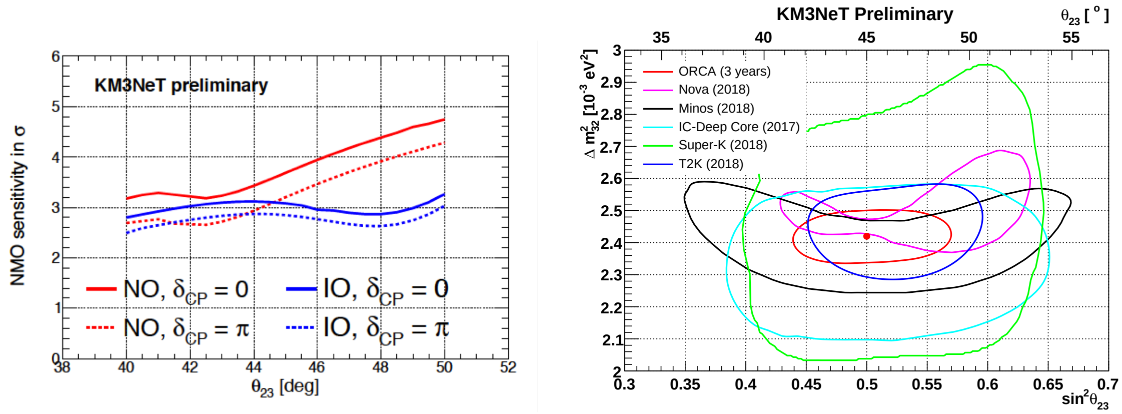

Figure 1: *(left) The projected NMH sensitivity for a 115 string ORCA detector after 3 years, as a function of θ_{23} and the CP phase. (right) ORCA one sigma contours, after three years, of the atmospheric neutrino oscillation parameters for the NH scenario (red). Contours from other experiments are also indicated.*

of θ_{23}, the absolute masses, whether they are their own anti-particle (i.e. Majorana or Dirac type), the value of CP phase and finally the neutrino mass hierarchy (NMH).

The ORCA array will measure about 50,000 atmospheric neutrinos per year in the energy range between 1 and 100 GeV. The majority of the neutrinos events are due to electron and muon neutrino and antineutrino charge-current (CC) interactions with tau neutrinos and neutral current (NC) interactions representing minor backgrounds. At E_ν= 5 GeV more than 50% of the events of the muon CC events detected by ORCA can be correctly identified as muon neutrinos, while less than 15% of electron neutrino CC events are misidentified as muon neutrinos. ORCA provides a neutrino energy resolution of about 30% and a zenith resolution about 7° (at E_ν=5 GeV).

2.1 Neutrino Mass Hierarchy

The NMH is termed "normal" (NH) if $\nu_1 < \nu_2 < \nu_3$ or "inverted" (IH) if $\nu_3 < \nu_1 < \nu_2$. Knowledge of the NMH is an important discriminant between theoretical models of the origin of mass. The NMH serves as an input to cosmological models and neutrino flavour conversion in supernovae explosions. Furthermore, the rates of neutrinoless double beta decay depend strongly on the NMH. Finally, the NMH has a significant impact on the precision determination of the PMNS parameters.

ORCA relies on the presence of matter effects that modify the ν_μ survival probability and the rate of $\nu_\mu \to \nu_e$ appearance at the atmospheric mass scale. The matter effects arise from the ν_e component of the "beam" undergoing charged-current elastic scattering interactions with the electrons in the matter. This effectively modifies the observed mixing angles and mass differences in a way that depends on the NMH [3].

Fig.**??** (left), shows the expected performance of ORCA to determine the NMH as a function of the assumed θ_{23} and CP phase. For a true IH the significance is essentially independent of θ_{23}. For a true NH, the significance improves as θ_{23} increases. If the current value of θ_{23} from the global fits of around 42° is assumed, ORCA will determine the hierarchy with a median significance of 3 sigma in approximately three years. The ORCA data are relatively insensitive to the CP phase, the significance being reduced by at most 20-30% depending on the true value of δ_{23}. As detailed in Ref. [1] many of the possible systematic uncertainties (oscillation parameters, CP phase, overall flux factor, NC scaling, ν/anti-ν skew, μ/e skew, energy slope) are actually fitted from the data itself when determining the NMH.

As explained in Ref.[4] there is a synergy between the ORCA and JUNO approaches based on the fact that when data are analysed with the wrong neutrino mass ordering the best fit occurs at different values of Δm^2_{31}. Hence, the wrong mass ordering can be excluded by a mismatch of the values inferred for Δm^2_{31}, thanks to the excellent accuracy for Δm^2_{31} of both experiments. The synergy effect may lead to a high significance determination of the mass ordering even in situations where the individual experiments obtain

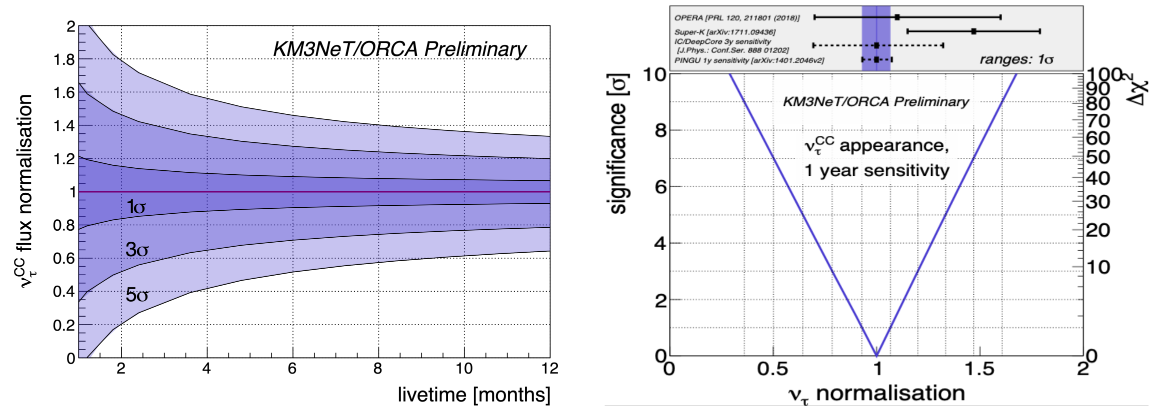

Figure 2: *Precision on the rate of ν_τ appearance as a function time. The true value is assumed to be the Standard Model expectation (1.0). The corresponding 1, 2, 5 sigma regions are indicated.*

only poor sensitivity.

Throughout the full range of neutrino oscillation parameter space, the complementarity of ORCA, beam and reactor experiments provides the surest path to determining the NMH, with synergistic effects that can improve the combined significance beyond purely statistical addition of results. Consistency of the results obtained from several of these experiments would provide assurance that our interpretation of the results in the three-flavour neutrino paradigm is indeed correct.

2.2 Oscillation parameters

Despite providing the first evidence for "atmospheric" neutrino oscillation, the mixing between the second and third neutrino mass eigenstates is currently the least well measured of the oscillation parameters in the neutrino sector. ORCA will measure $\sin^2\theta_{23}$ and Δm^2_{32} parameters via the disappearance of ν_μ in the atmospheric flux. Fig.1 (right) shows the expected precision after three years and compares it with current measurements. The precision of ORCA is comparable or better, and is obtained at much higher energies and longer baselines and with very different systematic uncertainties.

The current measurements of θ_{23} indicate that the angle is close to maximal mixing. If θ_{23} is not maximal, determining its value and its "octant" is of importance for understanding the origin of neutrino masses and mixing. Although in two-flavour models, values of θ_{23} above and below 45° produce identical transition probabilities, this is no longer true for three-flavour oscillation in the presence matter effects. By comparing the rates for neutrinos passing the Earth's core/mantle, ORCA can determine the octant for a wide range of θ_{23}. Unlike the case of T2K and NOVA, the measurement is essentially insensitive to the assumed CP phase.

2.3 Tau Appearance

The unitarity of the PMNS matrix is currently only tested at the 20%-40% level. Many Beyond the Standard Model theories, with an extended mixing matrix, could modify the rate of ν_τ appearance relative to Standard Model expectations. For vertically upgoing neutrinos, with a baseline of the Earth's diameter, the ν_μ disappearance into ν_τ is maximum around 24 GeV, well above the ORCA energy threshold. ORCA will detect around 3,000 ν_τ CC interactions per year. As shown in Fig.2, this yields a better than 10% precision on the ν_τ appearance rate with one year of data taking.

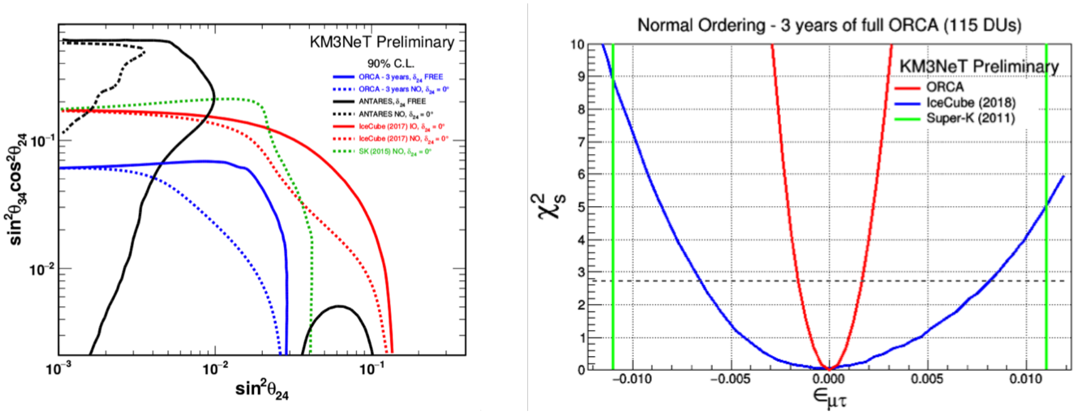

Figure 3: *(left) Preliminary one-year sensitivity of ORCA to sterile neutrinos. The regions on top-right of the curves are excluded. (right) constraints on the NSI $\epsilon_{\mu\tau}$ parameter.*

2.4 Sterile neutrinos and non-standard interactions

Phenomenological extensions of the standard 3ν oscillation framework can include non-standard interactions (NSI) that behave as four-fermion point interactions at low energies. For the sterile neutrino case, the Hamiltonian is extended to four neutrinos and the 4th neutrino is assumed not to interact. Fig.3 (left), shows the expected ORCA sensitivity to a single additional sterile neutrino; a significant improvement over existing measuerments is obtained. Fig. 3 (right) illustrates the sensitivity improvement on the $\epsilon_{\mu\tau}$ parameter compared to current limits.

2.5 Dark matter, Tomography

Observations in astronomy and cosmology provide irrefutable evidence that the vast majority of the matter in the Universe comprises non-luminous "dark matter" the nature of which is completely unknown. A theoretically well-motivated candidate is a Weakly Interacting Massive Particle (WIMP), but theory gives little guidance for the mass or whether their interaction with matter is dominantly spin-dependent or spin-independent. WIMPs could be captured in the massive objects such as the Sun or the Galactic Centre, accumulate and self-annihilate producing a flux of neutrinos, whose flux and maximum energy depends on the WIMP mass. Since the Sun is primarily made of protons, ORCA can place strong constraints on the spin-dependent WIMP-proton scattering cross-section (Fig.4 (left)), thereby extending the limits provided by ANTARES, IceCube and Super-Kamiokande to lower WIMP masses.

ORCA will also provide tomographic information on the electron density of the Earth interior [5]. This new technique is complementary to standard geophysical methods that probe mass density. As shown in Fig.4 (right) after 10 years of operation, ORCA can measure the electron density to $\pm 5\%$ for the lower mantle and $\pm 7\%$ in the outer core.

2.6 CP violation?

In its current configuration ORCA has little sensitivity to the CP phase. A new idea is being explored to fire a beam of neutrinos from the Protvino accelerator near Moscow to the KM3NET/ORCA detector and/or densified (Super-ORCA) versions (see [6] for details). It turns out this energy/baseline combination is optimal for decoupling the mass hierarchy and CP violation effects. The large instrumented volume of ORCA allows the intensity of the neutrino beam to be lower than that of conventional long baseline experiments, significantly reducing costs compared to other planned efforts.

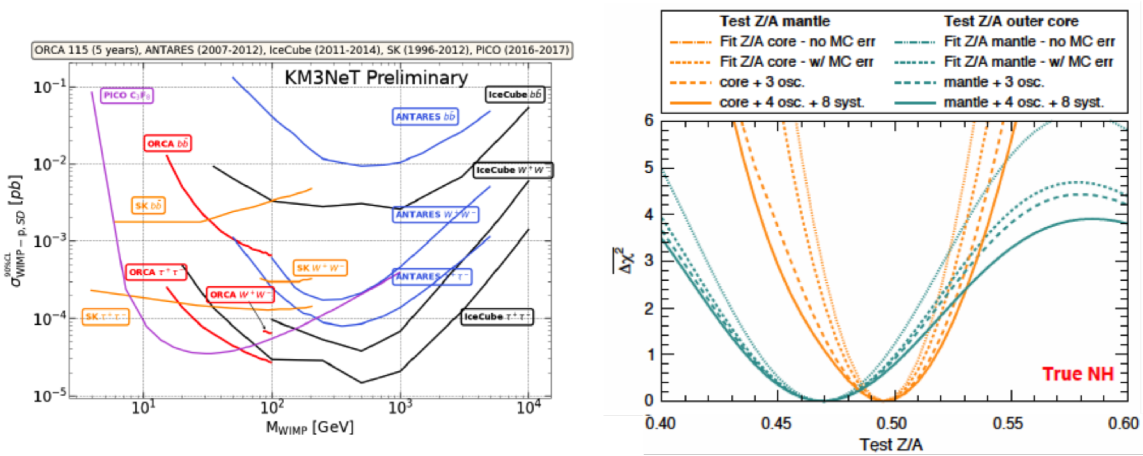

Figure 4: *(left) 90% C.L. limits on the spin-dependent WIMP-proton cross-section after 3 years of data taking, based on counting both ν_μ and ν_e events coming from the direction of the Sun. (right) Ten year $\Delta\chi^2$ profiles for mantle (orange) and outer core (blue).*

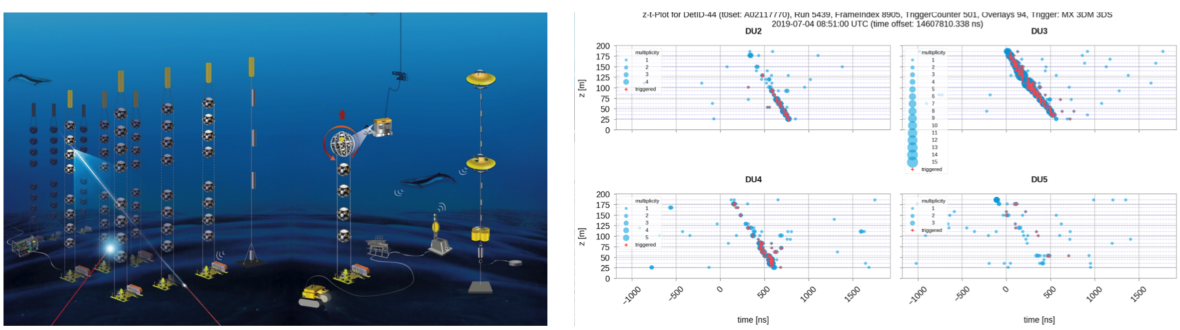

Figure 5: *(left) Artists view of the KM3NeT/ORCA detector. (right) A downgoing atmospheric muon event detected by 4 detection units.*

3 KM3NeT/ORCA Status

At present, the Collaboration consists of more than 240 persons from 52 institutes and 16 countries (Australia, Cyprus, France, Georgia, Germany, Greece, Ireland, Italy, Morocco, Netherlands, Romania, Russia, Spain, South Africa, Poland, United Kingdom). The french IN2P3 groups involved are APC, CPPM, IPHC, LUPM, Subatech. For the ESS activities, scientists from MIO-Marseille (AMU/INSU), Toulon University, DT/INSU-La Seyne-sur-Mer, Geoscience-Azur (INSU), IPGP (INSU) and Ifremer are involved through the framework of EMSO-France.

The Collaboration is preparing for mass production of detection units with production sites in most of the European institutes. In France, optical modules are produced in IPHC and Subatech, base containers in LUPM+CPPM, the calibration unit in APC and deployment and detector operations managed by CPPM. As of September 2019, the main electro-optic cable, a junction box and four neutrino detection units are operational on the KM3NeT/ORCA site. The equipment (Fig.5) is providing high quality data; for example a depth dependence of the muon flux was recently submitted for publication [7] . Two additional detection units will be deployed before the end of the year and a second junction box soon after. Assuming the construction rate is not limited by available funds the full array of 115 detection units will be completed by 2024. Note that interesting physics results will be forthcoming with a partial detector during the construction period.

4 Summary

Capitalising on the twenty years of experience acquired with the pioneering ANTARES neutrino telescope and many years of R&D effort, the KM3NeT Collaboration has developed a cost effective and performant technology to instrument large volumes of the deep sea. The technical implementation have been successfully demonstrated and large scale production of detection units and the corresponding extension of the sea floor infrastructure is underway. The infrastructure will offer innovative and synergetic opportunities for Earth and Sea Science studies. Using this technology two major physics questions will be addressed, namely the astrophysical origin of cosmic rays and the fundamental properties of the neutrino. In particular, the ORCA array, located in France, will allow the IN2P3 to be at the forefront of neutrino physics over the next decade.

References

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