High energy neutrino detection with KM3NeT

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Abstract. The KM3NeT Collaboration has started the construction of a next generation high-energy neutrino telescope in the Mediterranean Sea: the largest and most sensitive neutrino research infrastructure. The full KM3NeT detector will be a several cubic kilometres distributed, networked infrastructure. In Italy, off the coast of Capo Passero, and in France, off the coast of Toulon. Thanks to its location in the Northern hemisphere and to its large instrumented volume, KM3NeT will be the optimal instrument to search for neutrinos from the Southern sky and in particular from the Galactic plane, thus making it complementary to IceCube. In this work the technologically innovative component of the detector, the status of construction and the first results from prototypes of the KM3NeT detector will be described as well as its capability to discover neutrino sources are reported.

1. Introduction

The KM3NeT infrastructure [1] is a network of neutrino telescopes distributed among different sites in the Mediterranean Sea: ARCA-KM3NeT, dedicated to the identification of high energy neutrino sources and to the study of the cosmic neutrino flux measured by IceCube; ORCA-KM3NeT [3], designed for neutrino mass hierarchy studies. The flexibility of the KM3NeT technical project allows for using an almost identical detection structure. This contribution is mainly dedicated to the ARCA infrastructure.

2. The ARCA-KM3NeT high-energy neutrino telescope

The working principle of neutrino telescopes is based on the detection of Cherenkov light in an optically transparent medium (like ice or water) induced by charged particles generated in neutrino interactions. The light is recorded by a large number of photomultipliers arranged in a three-dimensional array.

The arrival time of the photons on the different photomultipliers allows for reconstruction of the neutrino direction, the measured light intensity for the reconstruction of the neutrino energy. The recent observation from IceCube of neutrino events with energy in the range between 30 TeV and 2 PeV [2] represents the evidence of extraterrestrial neutrino events and the beginning of neutrino astronomy. The question from where the detected neutrinos come will be a crucial question to be answered in the next years. The future high-energy KM3NeT telescope (ARCA), given its excellent angular resolution, can set important constraints on the origin of these neutrino events.

The KM3NeT telescope consists of an array of Digital Optical Modules (DOMs) [4] attached to vertical structures, called detection units (DUs) [5]. The average distance between DUs is
90 m. Each DU carries 18 DOMs, starting 70 m above the sea floor and with 36 m distance between adjacent DOMs. An array of 115 DUs will constitute a detector building block. The ORCA infrastructure differs in the distance between DUs and between DOMs in each DU, resulting in a denser array, more suitable for low energy neutrino studies. The DUs are supported by two prestretched Dyneema ropes and kept straight by a submerged buoy at their top. A single vertical electro-optical cable (VEOC) is used to connect the DOMs to the base of the DU. It consists of a flexible, oil-filled hose that is in equi-pressure with the sea water and contains optical fibres for data transmission and copper wires for electrical power provision.

For the deployment, a DU will be wrapped on a spherical frame with diameter of about 2.2 m (Launcher of Optical Modules, LOM [6]) which is deposited on the seabed and then unfurls in a rotating upwards movement. The LOM rises to the sea surface, where it is collected for reuse. The DOMs must withstand pressure up to about 500 bar, be resistant to corrosion and stress (vibration, shocks) during handling and deployment. Each DOM is a pressure-resistant glass sphere of 17 inch diameter that carries 31 3-inch photomultiplier tubes (PMTs) with their high-voltage bases as well as calibration devices and readout electronics. The novel design of DOM offers significant improvements with respect to optical modules with a single large area PMT: (i) the total photocathode area is about three times larger; (ii) a segmented photocathode allows for high-purity photon counting and directional sensitivity; (iii) reduced cost and risk; (iv) almost $4\pi$ solid angle coverage by each DOM.

All the necessary electronics for digitization and data transmission is contained within each DOM. The position calibration of each DOM is achieved at about 10 cm precision using acoustic triangulation. The acoustic system includes transponders at the seabed and a receiver in each DOM. All PMTs are calibrated and characterized before being used in the production of DOMs [7].

A schematic view of a DU is shown in Fig. 1.

![Figure 1. View of KM3Net Detection Units with Digital Optical Modules.](image)

The KM3NeT detector construction foresees a staged implementation:

- **Phase 1** consists of 0.2 blocks and its primary deliverable is the proof of feasibility and the first physics results. 7 ORCA-like strings and 24 ARCA-like strings will be deployed by the end of 2016;
- **Phase 2** consists of 2 ARCA-like blocks and 1 ORCA-like block.

During the preparation of these proceedings a full DU has been deployed at the Italian site on December 3rd, see 2. All eighteen DOMs are working properly and data taking started smoothly. Muon tracks have been reconstructed after few hours data taking started.
3. Results from a small detector unit prototype

A prototype DU has been installed at 3500 m depth 80 km offshore the Italian coast. This prototype has a height of 160 m (the full DU is 700 m height) with three DOMs and it is taking data since its deployment in May 2014. Details on the results are available in [8]. The intra-DOM offsets of the PMTs inside every DOM is determined from coincidences from $^{40}$K decays. The radioactive decay of the $^{40}$K contained in sea water produces a few hundred Cherenkov photons emitted along the track of the electron released in the decay and constitutes the main source of signal detected by the DOMs.

To calculate the inter-DOM time offsets (between DOMs) dedicated runs with a LED nanobeacon positioned in the top half of the upward-pointing DOM have been performed. The inter-DOM time offsets depend on the electronics plus the cable lengths. The travel time of light in sea water must be taken into account in this calibration procedure. To calculate the travel time of the nanobeacon light, the distance between the nanobeacon and the hit PMT is used. A fixed detector position is assumed, as a real time positioning system is not available for this prototype. The time accuracy achieved is of the order of $\sim 1$ ns [8].

The two main contributions to the single rates are the $^{40}$K decay and the bioluminescence activity. While the $^{40}$K decay is stable as a function of time and position, the bioluminescence activity can fluctuate significantly in time. A dedicated Monte Carlo (MC) simulates the expected atmospheric muon flux at a depth of 3457 m, together with the optical background due to the $^{40}$K decay. The PMT characteristics and the optical water properties measured at the Capopassero site are taken into account in the simulation. The optical background from $^{40}$K decays and bioluminescence dominate the coincidence rates in a DOM up to 5 coincidences, while muons are the dominant source at higher coincidences. Fig. 3 (a) shows the rate of events as a function of the coincidence level in a DOMs for data and MC simulation. The full Monte Carlo reported in Fig. 3 (a) refer to the sum of atmospheric muon events and $^{40}$K only events. No normalization factor is applied to the MC events thus showing an absolute excellent agreement between data and MC simulations. A distribution of hits as a function of the PMT orientation is show in Fig. 3 (b) compared to the distributions of the muon MC simulation. A cut for coincidence level $> 7$ is applied. Muon simulation is in a good agreement with data.

In Fig. 4 (a) the difference between the reconstructed and the true zenith angle is plotted using MC muon events; a FWHM of 7.6$^\circ$ is achieved. The distribution of $\cos \theta$ for the selected events is shown for data and Monte Carlo in Fig. 4 (b) demonstrating a good agreement.
4. Performances and physics objectives
The first physics goal of KM3NeT will be the investigation of the IceCube findings [2] from a complementary field of view and with better angular resolution. Evaluation of the telescope performance has been carried out using complete Monte Carlo simulation, including the neutrino interaction in the medium, the propagation of the resulting secondary particles, the Cherenkov light generation and propagation in water and the detector response. Depth and the optical water properties measured at the Italian site have been used [9]. Background due to the presence of $^{40}K$ in water was simulated adding an uncorrelated hit rate of 5 kHz per PMT plus higher-fold coincidence rates as determined by GEANT simulations and in agreement with the results from the prototype optical modules. KM3NeT is sensitive to all neutrino flavors, since events of different topology can be detected and identified: track-like events, generated mainly by $\nu_\mu$ Charged Current (CC) interactions, and shower-like events, such as those generated in $\nu_e$ CC and in all flavors Neutral Current (NC) interactions, provided that the interaction occurs inside or close to the detector volume. An isotropic one-flavour flux $\Phi = 1.2 \times 10^{-8}(E/\text{GeV})^{-2} e^{-(E_{\nu}/3\text{PeV})}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, as reported in [2], is assumed.
this channel (shown as a shaded area in the figure) is represented by the uncertainty on the conventional atmospheric neutrino flux. The shower channel gives a much better sensitivity, reaching a $5\sigma$ significance after less than one year. A combined analysis, incorporating the results from both search strategies has also been developed, giving as a final result a significance of 4.8$\sigma$ in 0.5 years of observation.

The sensitivity for the detection of galactic sources has been determined using as a test case the very intense SuperNova Remnant gamma source RXJ1713.7-3946 [10] and the Pulsar Wind Nebula Vela-X [11]. The neutrino energy spectrum was estimated from the gamma-ray spectrum assuming a 100% hadronic mechanism and a source transparent to gamma-ray emission according to [12] for RXJ1713.7-3946 and [13] for Vela-X. Under these assumptions, the significance of the source observation, with a 50% probability, as a function of the observation time for KM3NeT has been calculated [14] and is shown in Fig. 6. An observation with 3$\sigma$ significance is expected after about 2.5 and 4 years for Vela-X and RXJ1713.7-3946, respectively. The extension of the KM3NeT telescope to final configuration of six detector blocks will allow to reach a 5$\sigma$ significance after about 2.5 years for Vela-X and 4 years for RXJ1713.7-3946.

Figure 6. Significance of RXJ1713.7-3946 and Vela-X observations as a function of the years of data taking for KM3NeT.

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