The KM3NeT neutrino telescope

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Abstract. The construction phase of an underwater high energy neutrino telescope in the Mediterranean Sea, named KM3NeT, has started. The neutrino telescope that will consist of several blocks of instrumented structures will have a size of the order of a cubic-kilometer. In this work the main elements of the detector, the status of the project and the expected performance will be briefly reported.

1. Introduction

The detection of high energy neutrinos from astrophysical sources is the main physics objective of the KM3NeT detector. The study of high energy neutrinos produced in galactic and extragalactic sources can shed light on the production mechanisms of high energy particles and, if neutrinos are detected from specific sources, can give important constraints on the acceleration models. Moreover, the detection of neutrinos will give a clear signature of the presence of hadronic processes in the production of high energy particles [1]. In a multi-messenger approach the detection of high energy neutrinos will also shed light on the still unknown origin of the observed high energy cosmic rays and high energy γ-rays. High energy γ-rays can be produced both in hadronic and leptonic mechanisms. Moreover, extragalactic γ-rays, due to their interaction with the intergalactic environment, arrive at the Earth with a reduced flux and a distorted energy spectrum. The high energy cosmic rays, that are mainly protons, are deflected by the intergalactic magnetic fields and cannot be used to point back to the sources. Neutrinos that are neutral and weakly interacting particles are neither deflected nor absorbed and can reach the Earth carrying important information on the far and violent Universe.

From the experimental point of view the detection of high energy neutrinos is a challenging task. Large detectors with size of the order of a cubic-kilometer and a very low background are necessary. The most effective technique to detect neutrinos in the energy range between 100 GeV and 100 PeV is based on the detection, by means of optical sensors, of Cherenkov photons emitted by secondary particles produced in the neutrino interactions occurring in the volume inside or surrounding the detector. To maintain the background on a reasonable level the detectors have to be shielded from the particles produced in the interaction of cosmic rays with the atmosphere. To satisfy these requirements the high energy neutrino detectors are placed under thousands of meters of ice or water. To date the IceCube detector [2], with the size of about 1 cubic-kilometer is operating at depths ranging from 1450m to 2450m in the South Pole ice. With the IceCube detector a high energy neutrino flux of astrophysical origin has been discovered [3, 4]. Even if the origin of these neutrinos is still unknown this measurement has set the starting point of neutrino astronomy.
Strengthened by the experience gained with the construction of the small detector ANTARES [5], that is taking data since 2008, the three Mediterranean collaborations (ANTARES, NEMO and NESTOR) in 2006 started the R&D for the construction of a multi cubic-kilometer detector: the KM3NeT detector. Due to its location KM3NeT is the ideal instrument to look for neutrinos from point-like Galactic sources. In fact at the latitude of the Mediterranean Sea it is possible to detect neutrinos with a low energy threshold (about 100 GeV) over a large field of view (about 3/4 of \( \pi \)) with an almost complete view of the galactic plane. The collaboration has defined the design and has started the construction of a research infrastructure hosting a high energy neutrino telescope and nodes for Earth and Sea sciences. The physic case was recently extended to the measurement of the Neutrino Mass Hierarchy with atmospheric neutrinos, and a feasibility study, called ORCA, was started. From this study the best sensitivity to measure the Neutrino Mass Hierarchy is obtained with a dense Mton detector that can measure atmospheric neutrinos in the GeV region using the same KM3NeT technology with a much denser optical displacement. An experimental proposal for a multi-site experiment is underway. In particular a Gigaton detector for high energy astronomy is planned at the Capo Passero Italian site while a Mton denser detector is planned in the Toulon French site.

In this paper the detector technology and the status of the project will be briefly described, focusing on the performances of the Gigaton detector for neutrino astronomy. A description of the ORCA feasibility study can be found in [6].

2. The KM3NeT technology

The KM3NeT detector consists of a three dimensional grid of optical sensors. From the measured arrival time of Cherenkov light at each optical sensor, combined with the measured spatial positions it is possible to reconstruct the trajectory of the muons producing Cherenkov light with a very good angular resolution (few tenths of a degree). In addition the amount of detected light can provide information on the energy of the particle. The optical sensors, the Digital Optical Modules (DOMs), are attached to vertical structures, called Detection Units (DUs). The DUs are flexible structures anchored to the sea floor, kept vertical by buoys and connected to shore by an electro-optical cable (Fig.1). An array of 115 DUs will constitute a detector building block. Several building blocks will constitute the detector. Simulation results show that the division into separate building blocks does not affect the expected sensitivity, while it allows for a distributed detector implementation. The choice for a distributed research infrastructure made of several building blocks with common detector technology, management, data handling and operation control was based on both technical and funding-related arguments. Moreover, the distributed infrastructure is the preferred choice of the Sea and Earth Science community that profit from KM3NeT infrastructures to construct a network of sensors in the Mediterranean Sea.

A building block of the detector devoted to high-energy neutrino astronomy is composed by 115 DUs spaced on average by 90-120m. Each DU hosts 18 optical sensors, the Digital Optical Modules (DOMs), starting 100m above the sea floor and with 36m of vertical distance between adjacent DOMs. The definition of the distances between DUs and between DOMs is the result of a detailed optimization. The optimization, performed by means of Monte Carlo simulations, was focused on the primary objective of the Gigaton experiment: the observation of neutrinos from galactic point-like sources. The DUs are supported by two parallel Dyneema© ropes. Also attached to the ropes is a single vertical electro-optical cable used to connect the DOMs to the base of the DU. It consists of a flexible, oil-filled plastic tube that is in equi-pressure with the sea water and contains 30 optical fibers for data transport and two copper wires for the provision of electrical power to the DOMs. For each DOM, a break-out box provides connection to one fibre and two wires. This configuration of a detection unit is usually referred to as a string. For deployment, a detection unit is wrapped on a spherical frame with diameter if about 2.2m.
(Launcher of Optical Modules, LOM [7]) which is deposited on the seabed and then unfurls in a rotating upwards movement. After the unfurling the LOM rises to the sea surface, where it is collected for reuse.

Each DOM is a pressure-resistant glass sphere of 17-inch diameter that carries 31 3-inch photomultiplier tubes (PMTs) with low power high-voltage bases [8] and read-out electronics [9]. Each tube is surrounded by a reflector that effectively increases the collection efficiency per PMT by about 27% [10]. The lower hemisphere of each DOM contains 19 of the PMTs, which are thus downward-looking, whereas the other 12 PMTs look upwards. The front-end electronics amplify the PMT signals and transform them into digital time-over-threshold information that is fed into the readout via optical fibres. All PMT signals above an adjustable noise threshold (typically the equivalent of 0.3 photo-electrons) are sent to shore, where event candidates are selected by online filters running on a computer farm. For further details on DOM electronics and data acquisition see [11]. The PMTs are supported inside the glass sphere by a structure while the optical contact is assured by optical gel. The DOM also contains three calibration sensors: a LED nano-beacon for time calibration that illuminates the DOMs above, a compass and tiltmeter for orientation calibration and an acoustic piezo sensor glued to the inner surface for position calibration. A drawing of the DOM is shown in Fig.2.

![DOM](image)

**Figure 1.** Drawing of DU and details of the DOM mounted into the string.

**Figure 2.** Drawing of the DOM.

This innovative photon sensor, which is the result of an intense R&D activity, has several advantages with respect to the conventional optical modules with one large PMT (10” diameter PMT). It houses three to four times the photo-cathode area in a single sphere and has an almost uniform angular coverage. Because the photocathode is segmented, the identification of more than one photon arriving at the DOM can be done with extremely high efficiency and purity allowing a good optical background rejection and providing a directional information on the arrival photons. These have been proved analyzing the data collected in the first DOM prototype that has been integrated in the instrumented line of the ANTARES detector [12].

3. Status of the KM3NeT project

The KM3NeT detector will be constructed with a staged approach. The KM3NeT-phase1, fully funded, is presently under construction and will reach a volume of about 0.1 km$^3$. A following phase, KM3NeT-phase1.5, will consist of a high-energy neutrino telescope of 2 building blocks of 115 DUs, with volume of about 1-1.6 km$^3$, depending on the DU spacing, and a dense detector
for the measurement of the Neutrino Mass Hierarchy. The aim is to extend KM3NeT to six building blocks with a size of about 3-4.8 km$^3$ (full KM3NeT detector).

After the deployment of prototypes both at the Italian [13] and in the French sites [12], that proved the feasibility of the new designed detector components, the KM3NeT collaboration started the construction of KM3NeT-phase1 in the first months of 2014. In the Italian site 24 DUs based on the string concept and 8 DUs following the a flexible tower concept [14] will be deployed. A first prototype tower has been already deployed at a depth of 3500 m and took data for more than one year. From the data collected in this period the first measurement of vertical atmospheric muon flux at a depth of 3500m was measured and published in [13]. The long-term measurements of the environmental parameters confirms the low bioluminescence level at the KM3NeT-It site [15]. The foreseen detector of 24 DUs together with the 8 towers at the KM3NeT-It site, when completed, will constitute the most sensitive neutrino telescope in the Northern hemisphere and will be equivalent to about 10% of the IceCube detector. The first tower was already successfully deployed in December 2014. For the next step in the construction of KM3NeT-It, funding will be requested for a detector of two building blocks of 115 DUs each and a total instrumented volume of about 1 km$^3$ optimized for the neutrino astronomy.

In parallel the collaboration is preparing the deployment of 7 DUs at the French site (KM3NeT-Fr). The first string is already assembled (see Fig.3) and it is ready for the deployment that is foreseen in May 2015. The remaining six strings will be configured according the outcome of the ORCA feasibility study, with a interspacing between DUs of the order of 20m and between DOMs of about 6 m, thus providing a demonstrator for the Neutrino Mass Hierarchy experiment.

![Figure 3. First string assembled.](image)

4. Physics performances
The (cosmic) neutrinos discovered by IceCube, that correspond to a flux of about $3.6 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ with a cutoff at about 3 PeV, were measured in the energy range between 10 TeV to about 1 PeV in [3]. In a more recent analysis [4] a consistent flux was measured with a lower energy threshold (about 1 TeV) but with a significant reduction in the fiducial detector volume. Many of these events are cascade events (shower of elementary particles) which are detected with a poor angular resolution ($10^\circ$-$15^\circ$) that prevents the possibility of source pointing. The question where the detected neutrinos came from is one still pending and many possibilities have been explored [16]. This discovery has led the KM3NeT collaboration to plan an intermediate step in the detector construction: the KM3NeT-phase1.5 that will consist of 2 blocks of 115 DUs with a volume of about 1-1.6 km$^3$ (depending on the DU spacing).
With its superior angular resolution, larger field of view and effective area it will allow to put some constraints on the origin of this diffuse neutrino flux. In Fig.4 the performances of the KM3NeT-phase1.5 detector is shown in terms of significance as a function of the observation time for the flux observed by IceCube. The significance for the cascade channel includes all the neutrino flavors and has been performed selecting tracks reconstructed in the full angular range ($4\pi$). The significance for the muon channel has been estimated for tracks reconstructed as up-going plus a small region of 10 degrees above the horizon. A significance of $5\sigma$ is obtained after one year in the cascade channel and after about 2.5 years in the muon channel for the flux reported by IceCube.

![Figure 4](image1.png)  
**Figure 4.** Significance as a function of the observation time for the detection of a neutrino diffuse flux corresponding to the signal reported by IceCube, in the up-going muon (black) and cascade (red) channels.  

![Figure 5](image2.png)  
**Figure 5.** Angular resolution for cascade events reported as a function of the true MonteCarlo neutrino energy. Shown are the median and the 68/90% intervals of the error distribution.

Recently a more performant cascade reconstruction code has been developed showing the angular resolution reported in Fig.5. A resolution of 3 degrees is shown at 20 TeV and decreases down to about 1 degree at higher energies. No systematic uncertainties are included in this evaluation.

The Super Nova Remnants RXJ1713 and Vela Junior and the Pulsar Wind Nebula VelaX are the most intense high energy gamma-ray sources and possible neutrino sources in the Galactic plane. The expected detection capability of the KM3NeT-phase1.5 neutrino telescope is reported for the RXJ1713 and VelaX in Fig. 6. These results were estimated in the hypotheses that the sources have a neutrino spectrum derived from the high energy gamma-ray spectrum following the hypotheses in [17] and in [18] [19] and that the spatial extension of the neutrino emission region is the same as for the measured gamma-rays. With the KM3NeT-phase1.5 detector a significance of $3\sigma$ can be achieved in about 4-6 years of observation while with the full KM3NeT detector (6 building blocks) a significance of $5\sigma$ can be achieved in few years of observation [20]. The discovery potential at $5\sigma$ level has been evaluated also for a generic point-like source with an energy spectrum proportional to $E^{-2}$ and is shown in Fig. 7 as a function of the source declination. The comparison with IceCube shows that KM3NeT not only complements but also overlaps the field of view of IceCube exceeding with more than one order of magnitude the IceCube sensitivity in the Southern hemisphere.
Figure 6. Significance as a function of the observation time for the detection of a neutrino diffuse from the RXJ1713 (blue) and the VelaX (red) sources.

Figure 7. Discovery potential at 5σ 50% probability for point like sources with a energy spectrum proportional to $E^{-2}$ for the KM3NeT-phase1.5 detector (red) and KM3NeT full detector (black) as a function of the source declination. The blue curve shows the discovery potential for the IceCube detector [21].

5. Summary
In this work the KM3NeT project has been briefly presented, the main technical components of the detector and performance described. The collaboration started the construction phase of the fully funded KM3NeT-phase1 that consists of 24 strings and 8 towers in the Italian site near Capo Passero (Sicily) and 7 strings in the French site close to the Toulon coasts. The first tower was already deployed and the first string is completely assembled and is ready to be deployed in the first months of 2015. Finally the detector potential for the detection of Galactic sources and the IceCube diffuse flux has been reported.

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