IL NUOVO CIMENTO **39 C** (2016) 241
DOI 10.1393/ncc/i2016-16241-x

Colloquia: IFAE 2015

The KM3Net project: A neutrino telescope in the depths of the Mediterranean Sea

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received 7 January 2016

Summary. — The KM3NeT Collaboration has started the first phase of construction of a next generation high-energy neutrino telescope in the Mediterranean Sea. With several cubic kilometers instrumented and thousand of optical sensors, KM3NeT will be the largest and most sensitive high-energy neutrino telescope. 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. The full KM3NeT detector will be a distributed, networked infrastructure comprising several detector blocks. In Italy, off the coast of Capo Passero, and in France, off the coast of Toulon, the construction of the KM3NeT-It and KM3NeT-Fr infrastructures respectively is in progress. 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 and its capability to discover neutrino sources is reported as well.

1. – Introduction

Neutrinos represent an unique probe for the exploration of the high-energy universe. Even more than 100 year later the discovery of cosmic rays, the main question regarding the sources that can accelerate particles to energies far beyond what is achievable with man-made particle accelerators is still unanswered.

The detection of very high energy gamma rays allows to trace back their sources and to define eventual candidate sites of cosmic rays acceleration. But conclusions are often ambiguous because high-energy gamma ray photons, which can be produced in the interaction of cosmic rays with matter and photon fields, indicating the acceleration sites, can also be generated through the Inverse Compton Scattering mechanism of low-energy photons by accelerated electrons. From the observation of gamma ray spectra of two supernova remnants (W44 and IC443), the photons seem to originate from pion decay and hence from acceleration of protons or heavy nuclei [1]. A clear and definitive picture could be obtained with the detection of high-energy neutrinos.

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Thanks to its low interaction probability, neutrinos can propagate between the astrophysical sources and the Earth preserving the initial direction and energy. For the same reason is very hard to detect them, and it has become clear that huge detectors of cubic kilometer scale are necessary to exploit the physics potential of neutrino astronomy.

2. – Neutrino telescopes

The detection principle of neutrino telescopes, first proposed in 1960 [2], is based on the registration of Cherenkov light in an optically trasparent medium like ice or water induced by charged particles generated in neutrino interactions. The light has to be 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 allow for the reconstruction of the neutrino energy.

After the success with the demonstration of the detection principle with first underwater (BAIKAL [3] and ANTARES [4]) and under ice (AMANDA [5]) detectors, the design and the construction of large neutrino telescopes started. This led to the construction of the IceCube telescope [6] at South Pole, which in its final configuration, reached in 2010, consists of 86 strings with 5160 optical modules instrumenting $1\,km^3$ of clear glacial ice.

In the 2006 the Mediterranean neutrino collaborations (ANTARES, NEMO, NESTOR) started the R&D for the construction of a several cubic-kilometer detector: KM3NeT [7].

Thanks on its location in the Mediterranean Sea, the neutrino telescope, will be located in an optimal position to investigate neutrino fluxes from the Southern sky, in particular from the Galactic Centre and from a large fraction of the Galactic plane completing the field of view of the IceCube detector. The recent observation from IceCube of 37 neutrino events [8] (of which 15 are compatible with background), represents the evidence of extraterrestrial neutrino events and the beginning of neutrino astronomy. The question where the detected neutrinos come from will be a crucial issue of the next years and of future investigations. The future KM3NeT telescope, with its higher angular resolution, larger field of view and effective area can put important constraints on the origins of these neutrino event.

3. – The KM3NeT detector

The KM3NeT telescope consists of an array of Digital Optical Modules (DOMs) [9] attached to vertical structures, called detection units (DUs) [10]. The average distance between neighbouring DUs is 90 m. Each DU carries 18 DOMs, starting 100 m above the sea floor and with 36 m distance between adjacent DOMs. An array of 115 DUs will constitute a detector building block. Several building blocks will be installed at one or more installation sites at depths ranging from about 2500 m to 4500 m.

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 transport and copper wires for electrical power provision.

For deployment, a detection unit will be wrapped on a spherical frame with diameter of about 2.2 m (Launcher of Optical Modules, LOM [11]) which is deposited on the seabed

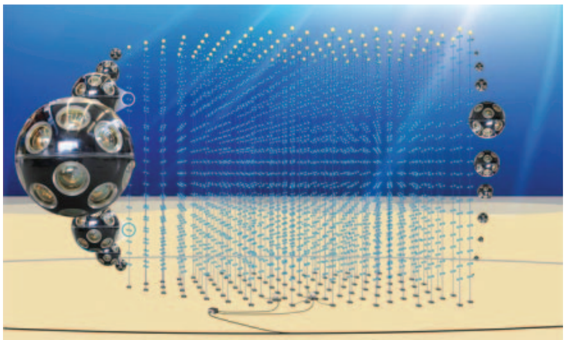


Fig. 1. – Schematic view of KM3Net Detection Units with Digital Optical Modules.

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. The lifetime of the detector should exceed 10 years and the reliability of the DOMs should be high. 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 lower hemisphere of each DOM contains 19 of the PMTs, which are thus downward-looking, whereas the other 12 PMTs look upwards. 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 4π 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 seafloor and a receiver in each DOM. A schematic picture of a KM3Net structure is shown in fig. 1.

Different types of PMTs, ETEL D783FL [12] and Hamamatsu R12199-02 [13], with comparable performances and slightly varying dimensions will be used for DOM assembly. Typical performances are a transit time spread lower than 5 ns (FWHM), quantum efficiency of 22% at 470 nm and 27% at 404 nm.

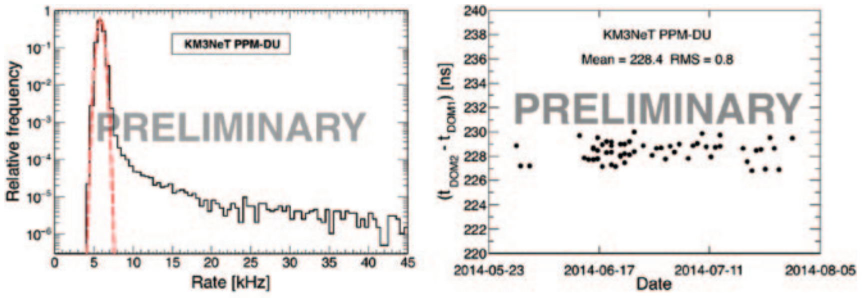
The PMTs are operated at a gain of 3×10^6. Dark count rates as measured in the laboratory at room temperature vary typically between 200 and 1500 Hz with a threshold of 0.3 photoelectrons. The gain adjustment is performed for all PMTs by finding the high-voltage setting which gives a ToT of 26.4 ns for a single photoelectron.

All PMTs are calibrated and characterized before being used in the production of DOMs [14].

4. – Results from a small detector unit prototype

A prototype Detector Unit 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 height) with three DOMs and is taking data since its deployment in May 2014.

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) (b)

Fig. 2. – (a) Mean photon rate measured by a PMT of DOM1. The Gaussian fit is superimposed and represent the optical background due to ^{40}K decay. The tail on the right is due to transient bioluminescent phenomena. (b) Mean time offsets for DOM2 with respect to DOM1 evaluated with the usage of nanobeacon of DOM1 for different runs.

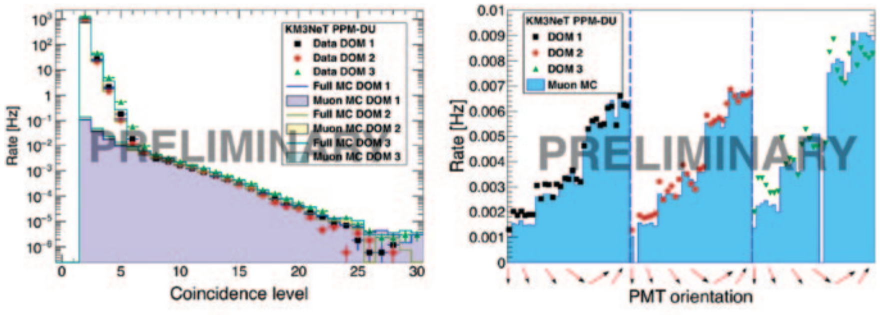
a few hundred Cherenkov photons emitted along the track of the electron released in the decay and constitutes the main source of signal detected by the DOMs.

To calculate the inter-DOM time offsets (between DOMs) dedicated runs with a LED nanobeacon activated are used. The LED nanobeacon installed in each DOM has a wavelength of 470 nm and is positioned in the top half of the DOM pointing upwards. The LED nanobeacons are controlled with adjustable frequency and intensity in order to illuminate the neighbouring DOM on the line without saturating the PMTs. 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 resulting mean time offsets for different runs are shown in fig. 2(b). The time accuracy achieved is of the order of ~ 1 ns.

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. The average singles rate per time slice of 134 ms for one PMT of DOM1 is shown in fig. 2(a).

A dedicated Monte Carlo 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 Capo KM3NeT-It 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. Figure 3(a) shows the rate of events as a function of the coincidence level in a DOMs for data and Monte Carlo simulation. The full Monte Carlo histograms 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 Monte Carlo events thus showing an absolute excellent agreement between data an Monte Carlo 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 Monte Carlo simulation. A cut for coincidence level > 7 is applied. Muon simulation is in a good agreement with data.

A dedicated algorithm to reconstruct the zenith angle of the direction of atmospheric muons has been developed. This algorithm uses the information about the position of



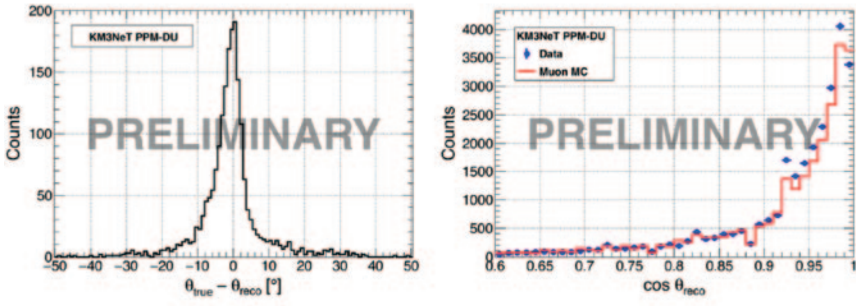
(a) (b)

Fig. 3. – (a) Rate of events as a function of the number of PMTs in coincidence compared to Monte Carlo simulation. (b) Rate of hits in each DOM as a function of PMT position for events with more than 7 coincidences on the respective DOM.

the three DOMs and the time of the local coincidences detected. Only muon events that trigger the three DOMs are reconstructed [15]). In fig. 4(a) the difference between the reconstructed and the true zenith angle is plotted using Monte Carlo muon events; a FWHM of 7.6 degrees 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.

5. – Performances and physics objectives of KM3NeT

The first physics goal of KM3NeT will be the investigation from a complementary field of view and with better angular resolution of the IceCube findings [8]. 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 KM3NeT-It site have been used [16]. Background due to the presence of ^{40}K in salt water was simulated adding an uncorrelated hit rate of 5 kHz per PMT plus



(a) (b)

Fig. 4. – (a) Zenith angular resolution of tracking algorithm obtained with Monte Carlo simulation. (b) Reconstructed $\cos\theta$ for data and Monte Carlo. The data sample used is equivalent to a livetime of $\sim$ 600 hours.

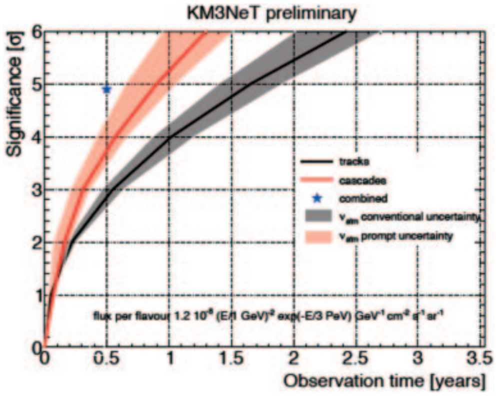


Fig. 5. – Significance as a function of the observation time for the detection of a diffuse flux of neutrinos corresponding to the signal reported by IceCube, in the up-going muon channel (black), the cascade channel (red) and the combined analysis (blue star).

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 ν_μ Charged Current (CC) interactions, constitute the "classic" detection channel. These events can be generated far from the detector, as high-energy muons can travel several kilometers in water. The identification of these events is however limited to up-going tracks due to the presence of the atmospheric muon background. Shower-like events, such as those generated in ν_e Charged Current (CC) and in all flavors Neutral Current (NC) interactions can also be detected, provided that the interaction occurs inside or close to the detector volume. An isotropic one-flavour flux $\Phi = 1.2 \times 10^{-8}(E/\mathrm{GeV})^{-2}e^{-(E_\nu/3\,\mathrm{PeV})}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, as reported in [8], is assumed.

Results referred to two building blocks are represented in fig. 5. For the track channel a significance of 5σ is reached after less than 2 years of observation. The major uncertainty for 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 5σ significance after less than one year. In this analysis, background due to atmospheric muons can be rejected applying geometrical cuts on the reconstructed interaction vertex (containment) and by an energy cut applied using the time over threshold information of the PMTs, which is correlated to the charge collected. The final step to select signal events is performed by a machine learning algorithm. The major contribution to systematic uncertainty for this channel is due to the uncertainty on the prompt neutrino flux. A combined analysis, incorporating the results from both search strategies has also been developed, giving as a final result a significance of 4.8σ in 0.5 years of observation.

Identifying Galactic neutrino sources is a priority physics goal with the full KM3NeT detector. 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 [17] and the Pulsar Wind Nebula Vela-X [18]. 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 [19] for RXJ1713.7-3946 and [20] for Vela-X.

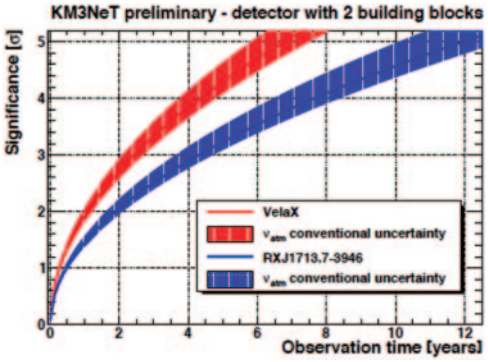


Fig. 6. – Significance of RXJ1713.7-3946 and Vela-X observations as a function of the years of data taking for KM3NeT.

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 [21] and is shown in fig. 6. An observation with 3σ 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 its final configuration of six detector blocks will allow to reach a 5σ significance after about 2.5 years for Vela-X and 4 years for RXJ1713.7-3946.

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