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Sensitivity of a multi-photomultiplier optical module for KM3NeT

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Elsevier use only: Received date here; revised date here; accepted date here

Abstract

For the KM3NeT neutrino telescope an optical module with a number of small photomultiplier tubes (multi-PMT optical module) will be advantageous for various reasons, e.g. reduced background rate, a larger number of coincidence hits, and sensitivity to ultra-high energy neutrinos. The properties of such a design have been investigated by measurements and simulations. Several types of 3" PMT were exposed to LED light pulses with intensities down to the single-photon level. The simulation tool Sirène for a photo-sensor based neutrino telescope has been applied to allow a comparison with the ANTARES detector. All muon directions can be observed with an improved identification and rejection of atmospheric muons. For up-going neutrinos and down-going muons the multi-PMT arrangement shows a better performance in both the photo-electron response and in the number-of-hits response as compared to the present ANTARES design.

PACS: 95.30.Cq, 95.55.Vj, 95.85.Ry, 29.40.Gx

Keywords: Elementary particle processes; neutrino detectors; cosmic rays; particle tracking;

1. Introduction

The ANTARES neutrino telescope has been completed recently and consists of 12 lines with 25 storeys. Each storey holds three optical modules (OMs), each housing a 10" Hamamatsu R7081-20 photomultiplier tube (PMT). As the primary goal is to detect upward going muons (and hence neutrinos), each PMT faces down at an angle of 45^{o} below the horizon. Because of the background rate in the sea

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and the dark noise from the PMT itself (≈2 kHz), different levels of triggering are used before a muon event candidate is stored. The first trigger level, “L0”, requires signals to surpass a threshold, individually set for each PMT, of a fraction (usually 1/3) of a single photo-electron (SPE). Out of these signals a “L1” trigger can be made either by requiring more than one PMT in L0 or more than a given number of photoelectrons (PE) per PMT. The multi-PMT optical module has been proposed [1] as an alternative to the ANTARES design. In this report the sensitivity of such a design will be discussed. Tests with several types of small 3” PMT’s have been performed and the results have been used for simulations of muon and neutrino detection [2].

2. The multi-PMT optical module

Subdividing the photo-sensitive area into a number of small photo sensors (PMTs) will be advantageous for several reasons:

1.) As the background rates are proportional to the photocathode surface, a sea background of 5 kHz to 10 kHz can be expected in a 3” PMT.

2.) The multi-PMT candidate has higher quantum efficiency (QE, 30% at 400 nm) than the R7081-20 (23% at 400 nm). A new type of photocathode with quantum efficiency of up to 45% at 400 nm is under development by Hamamatsu (ultra bialkali, UBA) and Photonis (super-photocathode).

3.) The segmentation of the detection area in the optical module will provide a larger number of coincidence hits per event. Compared to high-amplitude hits, this is favourable as the spread in the amplification of the electron-multiplier, especially for a large PMT, is rather high.

4.) A segmented detector surface leads to an increased hit statistics and a correspondingly improved timing accuracy.

5.) A multi-PMT layout of the OM will result in a more homogeneous coverage of incoming muon directions and add sensitivity for down-going muons.

6.) The down-going muon tracks allow better energy calibration based on atmospheric muons.

Furthermore, to observe ultra-high energy (UHE) neutrinos, down-wards going muon tracks need to be identified amidst the background of atmospheric muon tracks. The multi-element optical module will be beneficial for the detection of UHE neutrinos.

3. The multi-PMT arrangement

Inside one 17” hemisphere one can fit 20 PMTs of 3” diameter. PMT prototypes with convex shaped entrance window have been built to match the inside of the OM glass sphere by a flat silicon-rubber cookie. Styrofoam and silicon-rubber will absorb the deformation of the sphere by about 4 mm from the high pressure at the detector site. Since the space available for power supply and readout is constrained, a low-power high-voltage generating base with integrated readout has been developed at NIKHEF. Heat dissipation inside the sphere poses another challenge, which can be met [3] by suitably placed heat sinks and natural convection to keep the temperature at 12^{o}C above ambient temperature.

Also for UBA, the thermionic emission is expected to decrease by a factor of 2 for every 5^{o}C decrease in temperature.

Simulations [4] of a cylindrical PMT arrangement with 36 PMTs per storey have shown an increased effective area compared to the ANTARES storey. The transmission loss due to sedimentation and fouling decreases drastically for larger zenith angles and is estimated to be less than 5% per year at zenith angles larger than 20^{o}, while 2% per year was measured [5] at 90^{o}. Since space is needed for fixations and cable-connections, the PMTs near zenith angle 0^{o} can be easily left out of the setup. In subsequent simulations we apply optical modules containing 38 3” PMTs.

4. Measurements on the 3” PMT

Response measurements were performed in a temperature controlled dark box equipped with light fibre, mounted on a remote-controlled movable platform, and LED pulser [6]. With a trigger rate of 10 kHz pulses from single to several hundred photoelectrons could be produced. Signal traces were recorded with a sampling frequency of 2 GHz after maintaining PMTs for at least 12 hours in the dark box. Initial measurements were done with the XP53X2 9-stage PMT. However, to achieve a SPE signal well above the noise level required exceeding by far the nominal gain. Good timing characteristics (fig. 1) with transit time spread within 3 ns FWHM and a good peak-to-valley ratio were observed, however, at dark count rates of 6-10 kHz.

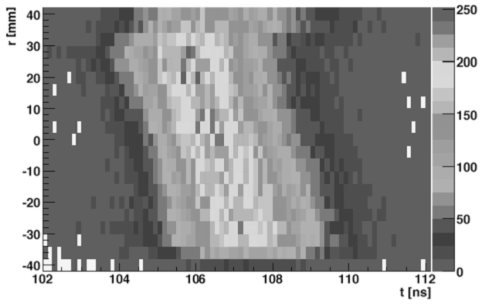

Fig.1. Transit time spread for XP53X2 at reference gain as function of the radial position on the cathode surface.

A modified XP53X2, the 10-stage XP53B2 PMT coated with a conductive layer on cathode potential, maintains the good timing behaviour and peak-to-valley ratio. Samples showed a dark rate of 1.1 kHz with a threshold at 30% of the SPE peak. This PMT therefore fulfils the necessary requirements on dark rate, timing properties and peak-to-valley ratio [7]. The integrated charge as a function of time-over-threshold shows a linear behaviour in the range of 1 to 8 SPE, thus covering the relevant range of expected signals.

5. Simulation with Sirène

The simulation package Sirène [8,9] generates Cherenkov photons and electromagnetic showers (ES) from muon tracks. Photons from these processes are tracked onto detector modules housing the photo sensors. The multi-PMT configuration with 38 3" PMTs and measured properties of XP53B2 PMTs has been implemented [2]. The angular coverage of one multi-PMT OM per storey is compared in fig. 2 with the coverage of 3 ANTARES PMTs. Muon neutrinos are generated by the Genhen [10] package and atmospheric muons by CORSIKA34 [11,12].
For low-energy (10^{10}-10^{16} eV) up-going neutrinos the mean number of hit PMTs per storey and per event is 1.3 for ANTARES and 2.5 for the multi-PMT module. Therefore, the chances to find coincidences of 2 or 3 hits in one storey are higher for the multi-PMT design. The larger ANTARES PMT has more high-amplitude hits, while the multi-PMT module has more hits involving only one photo electron per PMT. Figure 3 shows the number of photo-electron hits from low-energy neutrinos as a function of PMT ID for the multi-PMT setup (fig. 2).

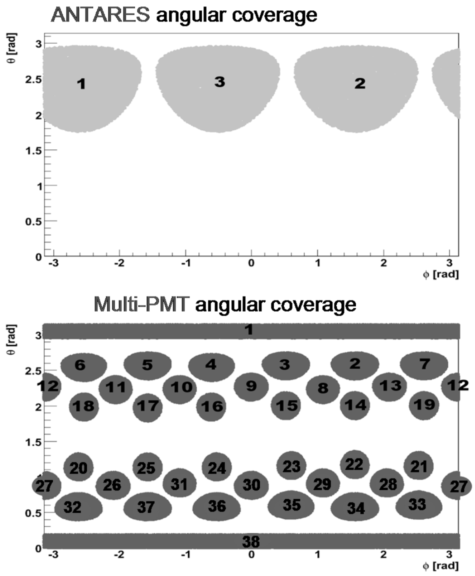

Fig. 2. Angular coverage in zenith (θ) and azimuth (ϕ) for the three PMTs in the ANTARES optical modules (top) and the 38 PMTs in the multi-PMT optical module (bottom) in one storey of a ANTARES detection line.

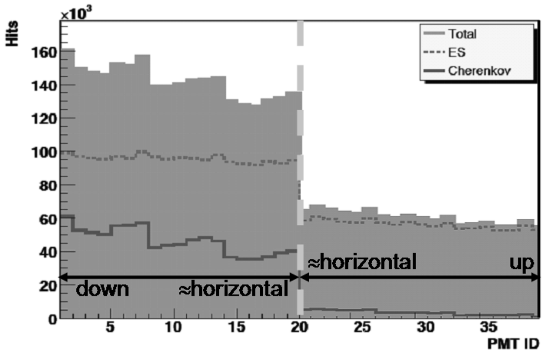

Fig. 3. Contributions from Cherenkov photons and photons from electromagnetic showers (ES) to the number of PE hits per PMT for low energy up-going neutrinos.

Cherenkov and electromagnetic shower photons are generated along the muon tracks. Cherenkov photons are almost exclusively detected at the bottom half of the OM. The photons from electromagnetic showers are more homogeneously spread over the whole module. Most of the photon hits originate from ES and this effect is even enhanced for high-energy (10^{15}-10^{17} eV) neutrinos. Half of the hits from the electromagnetic shower photons are unavailable to the ANTARES OM.

Muons are produced in the atmosphere by charged cosmic particles and enter the detector from above. The upwards oriented part of the multi-PMT is of eminent importance for detecting these muons. The fraction of Cherenkov photons is much higher than compared to the case with up-going neutrinos, because the initial energies are reduced as the first interactions take place in the atmosphere. The energy available to electromagnetic showers is even smaller and fewer particles are created. As a result, few photons are seen at the bottom-side of the OM and a low number of hits is expected in the ANTARES module (equivalent to PMT ID 2 - 19).

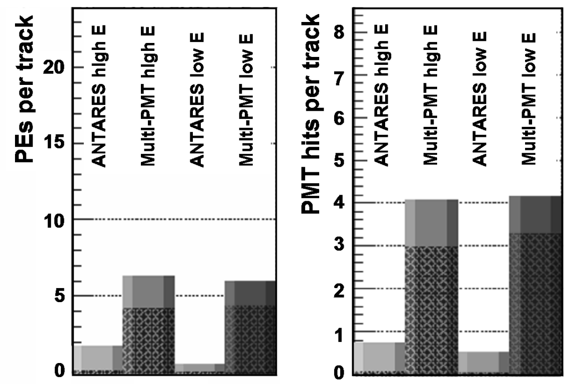

Fig. 4. Number of photoelectrons (left) and PMT hits (right) per track and per storey for down-going muons created by low- and high-energy protons. The fraction of Cherenkov photons has been indicated by the cross-hatched area.

In fig. 4 the sensitivities for the ANTARES and the multi-PMT OM are compared for both low-energy (10^{12}-10^{13} eV) and high-energy (10^{13}-10^{14} eV) protons creating muons in the atmosphere. Standard quantum-efficiencies (23% for ANTARES and 30% for the multi-PMT OM) have been used. As in the case of neutrinos, the observed effects are even more pronounced when applying a super-photocathode in the multi-PMT setup. It can be concluded that the multi-PMT arrangement is superior to the present ANTARES design in both the photo-electron and the number-of-hits response.

6. Summary

The multi-PMT optical module proposed for KM3NeT has been studied. The multi-PMT setup with measured PMT characteristics was implemented in the simulation program Sirène, which allowed evaluating the sensitivity. For up-going neutrinos the multi-PMT arrangement shows a better performance in both the photo-electron response and in the number-of-hits response as compared to the present ANTARES design. Most of the photon hits originate from ES and this effect is enhanced for high-energy neutrinos. Half of the hits from the electromagnetic shower photons are unavailable to the ANTARES OM. For down-going atmospheric muons the fraction of Cherenkov photons is much higher than compared to the case with up-going neutrinos. The multi-PMT arrangement is superior to the present ANTARES design in both the photo-electron and the number-of-hits response. As in the case of neutrinos, the observed advantageous effects are even more enhanced when a super-photocathode is applied in the multi-PMT setup.

Acknowledgements

This work is supported through the EU-funded FP6 KM3NeT Design Study Contract No. 011937.

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