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A new direction-sensitive optical module for deep-sea neutrino telescopy

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ABSTRACT

Within the KM3NeT framework, the NEMO (NEutrino Mediterranean Observatory) project is studying new technologies for a km^3-scale neutrino telescope in the Mediterranean Sea. The telescope goal will be the investigation of the high-energy component of the cosmic neutrino spectrum: a promising tool to better understand the mechanisms that originate extreme-energy cosmic rays. Neutrino energy and direction will be reconstructed using the Cherenkov light produced in water by muons coming from neutrino interactions. Two prototypes of a new large-area (10 in.) 4-anode photomultipliers, manufactured by Hamamatsu at the request of the NEMO Collaboration, have been extensively studied. These tubes will be integrated into spherical glass pressure-resistant optical modules and used for the first time to detect the direction of the detected Cherenkov light at the NEMO deep-sea (3600 m) site near Capo Passero in Sicily. The photocathode surface in these optical modules will be effectively divided into four quadrants by a pair of crescent-shaped mirrors embedded in the optical gel linking the PMT to the glass pressure sphere. A series of measurements was performed at the testing facility of the NEMO group at the INFN Sezione di Catania. The single photoelectron peak, the transit time spread, the gain and the cross-talk of the prototype have been studied, to have a complete characterization and make feasible a comparison with previous models. The first prototype of direction-sensitive optical module has been assembled and tested with a dedicated experimental setup at the INFN Sezione di Genova. First results of tests of the prototype are presented.

1. The deep-sea neutrino telescope

The deep-sea neutrino telescope is a particular kind of telescope, which uses very high energy radiation coming from extra-galactic sources to obtain information about sources' composition [1–4]. Due to its particular features (no electric charge and weak interaction with matter), the neutrino is not deflected along its path to Earth, thus representing a very good "astronomic probe" for extra-galactic sources. However, for high-energy neutrinos ($E_\nu > \text{TeV}$), the interaction cross-section is small, the expected flux is low and there is a consistent atmospheric muon background. The requirements of such a telescope are a large volume ($\simeq 1\,\text{km}^3$) and a consistent water shield. The Mediterranean Sea provides sites which satisfy these requirements and a northern telescope for high-energy neutrinos is under study by KM3NeT [5].

The KM3NeT underwater telescope structure consists of an array of sub-structures equipped with several light-sensitive elements, usually called optical modules (OM). The principle of the neutrino detection consists in collecting the Cherenkov light emitted by the muon produced by the interaction of the muonic neutrino with a nucleus. The light is collected by the optical modules and the signal is sent to the off-shore station via optical fiber cables. A lot of different geometries are under study for the KM3NeT telescope and one of these is NEutrino Mediterranean Observatory (NEMO)-KM3. This particular geometry is designed to have $(9 \times 9) = 81$ towers, each one equipped with 64 OMs located on 16 floors. This structure will be placed 3500 m below sea level, 80 km far from Capo Passero in Sicily.

2. The direction-sensitive optical module

All the traditional OMs have a very similar structure which allows a quite good track reconstruction if the number of hits is sufficiently high, i.e. 10 or more: this means that the track length must be sufficiently large. This is due to the intrinsically limited density of sensitive elements which can be achieved in such a kind of detector: a steep reduction of the efficiency under 1 TeV is the net effect for a cubic kilometer scale detector, with almost homogeneous OM distribution. Several new solutions are under study for KM3NeT optical modules, one of this is the direction-sensitive OM [6]. The idea is to use the direction information of the incoming light. The angular correlation allows to better determine the light emission point and simulations [7] show that it can increase detection efficiency up to a factor of two at low

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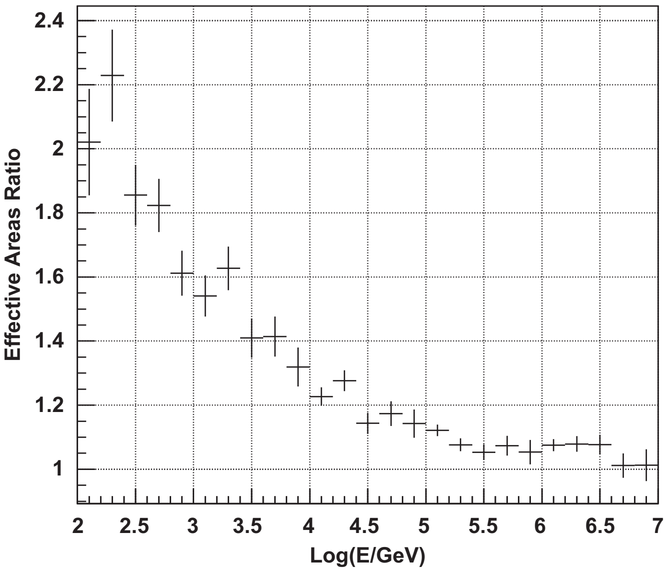

Fig. 1. Ratio of the effective areas calculated for a cubic kilometer detector with and without direction-sensitive OMs: a gain of a factor two is expected at low energy.

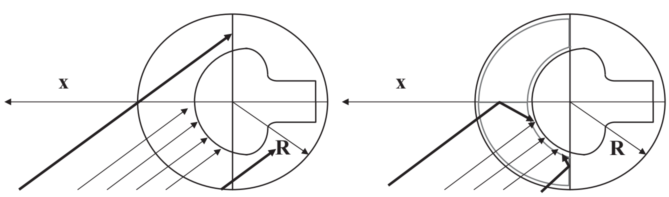

Fig. 2. A section of a direction-sensitive OM: if compared to a traditional one, the multi-anode PMT and the mirror system are the main difference.

Table 1
Performance of the 4-anode prototype compared to Hamamatsu R7081 [8,9].

	Requirement	R7081	Prototype
Nominal voltage (V)	<2000	1340	1550
Gain	$\sim 5\times 10^7$	$\sim 5\times 10^7$	$\sim 5\times 10^7$
Peak to valley ratio	>2	2.8	~3
Dark noise (thr. 0.3 pe) (kHz)	<10	0.9	~1.2
Transit time spread (ns)	<4	3	~4

neutrino energy, i.e. $E_\nu < 100$ GeV, and by several 10% between 100 GeV and 10 TeV (see Fig. 1). These results were obtained with a rough optimization of the reconstruction code: a more complete optimization is underway and we expect further improvements in the detector sensitivity. The structure of a direction-sensitive OM, shown in Fig. 2, is similar to a standard one: a large hemispherical PMT is hosted in a pressure-resistant glass sphere, optically coupled to the PMT using a layer of optical glue. The power supply and front-end electronics are included in the sphere and directly connected to the PMT. In order to be direction-sensitive an OM requires

- a position-sensitive detector and
- a light collimation system.

2.1. The 4-anode photomultiplier

Hamamatsu was asked to develop two prototypes of a 4-anode, 10 in. PMT. The photocathode surface is divided into four sectors each one connected to its corresponding anode by an independent dynode chain. The angular acceptance, compared to the one of a traditional PMT, shows a more constant behavior as a function of the angle of incidence. A series of measurement were performed at the testing facility of the NEMO group at the INFN Sezione di Catania [8,9]. The single photoelectron (SPE) peak, the transit time spread, the gain and the cross-talk of the prototype were studied to have a complete characterization and allow a comparison with previous models. A summary of these measurements is shown in Table 1.

Cross-talk between cathodes, due to focusing of the photo-electrons on the wrong dynode, is very small, of the order of few %. This can be evinced looking at the plot in Fig. 3 which represents the first anode response varying the position of a light source on the photocathode surface. The number of events corresponding to over-threshold signals has a maximum when the correlated sector of the photocathode surface is hit by the laser beam and it has a minimum when the laser beam hits the rest of the photocathode surface.

2.2. The light collimation system

The light collimation system was realized by depositing a very thin foil of highly reflective material over a substrate of plexiglas,

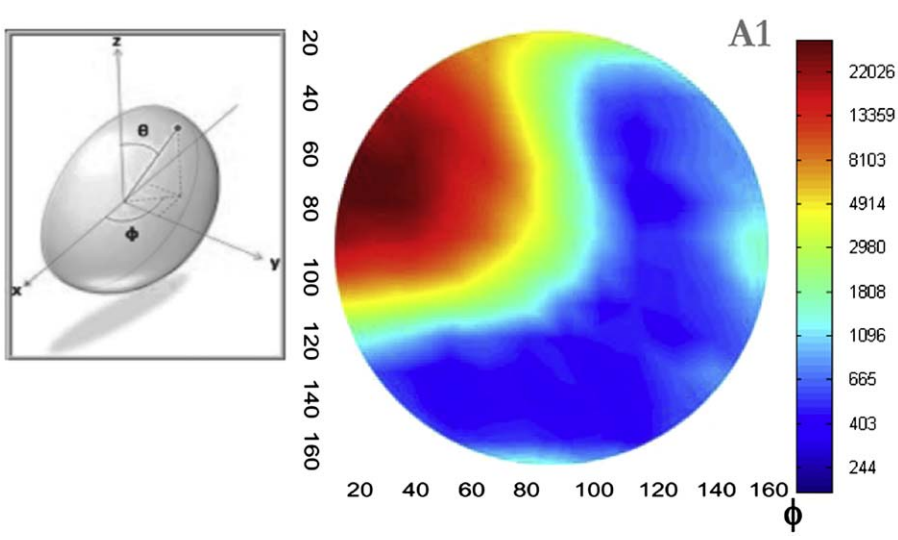

Fig. 3. First anode response as a function of the position of the light source on the photocathode surface. The center of the coordinate system is the center of the ideal sphere delimited by the photocathode surface (see top-left schema) [8,9].