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Measurement of the atmospheric muon flux at 3500 m depth with the NEMO Phase-2 detector

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Abstract. In March 2013, the Nemo Phase-2 tower was successfully deployed at 80 km off-shore Capo Passero (Italy) at 3500 m depth. The tower operated continuously until August 2014. We present the results of the atmospheric muon analysis from the data collected in 411 days of live time. The zenith-angle distribution of atmospheric muons was measured and results compared with Monte Carlo simulations. The associated depth intensity relation was then measured and compared with previous measurements and theoretical predictions.

1. Introduction

High energy neutrinos are considered optimal probes to identify the sources of high energy cosmic rays. Their detection is therefore one of the most interesting topics of astroparticle physics. High energy neutrino astronomy requires km^3-scale detectors because of the low expected neutrino fluxes [1]. After the first generation of neutrino telescopes, such as BAIKAL [2], AMANDA [3] and ANTARES [4], the IceCube telescope at the South Pole recently showed the first evidence for high energy extraterrestrial neutrinos [5]. The next step will be the construction in the Mediterranean Sea of a deep-sea km^3-scale detector: the KM3NeT telescope [6], result of a joined effort of the ANTARES, NEMO and NESTOR Collaborations, which conducted intense R&D activities. KM3NeT will be implemented as a distributed infrastructure in three sites: Toulon (France) [7], Capo Passero (Italy) [8] and Pylos (Greece) [9].

A first small-scale prototype, a tower-like detection unit (NEMO Phase-1 tower), was operated for five months during 2007 at 2080 m depth offshore Catania (Italy) [10]. In March 2013, a larger scale prototype (NEMO Phase-2 tower) was deployed in the Capo Passero site at a depth of 3458 m. This detector was continuously operated for more than one year. In this paper, after a description of the detector, we report on the measurement of the atmospheric muon angular distribution and on the comparison with Monte Carlo simulations. The corresponding muon depth intensity relation is evaluated and compared with theoretical predictions and with previous results. The present analysis extends the muon depth intensity relation measured in water up to 13 km.

2. The NEMO Phase-2 tower

The NEMO Phase-2 tower was deployed on March 23 2013 at the site located about 80 km offshore Capo Passero (latitude: $36^\circ\ 17'\ 48''$ N, longitude: $15^\circ\ 58'\ 57''$ E) at a depth of 3458 m. The tower operated continuously until August 4 2014, when it was disconnected to allow for an upgrade of the infrastructure. The tower is a three-dimensional flexible structure composed of eight horizontal *floors* interlinked by a system of tensioning ropes. The structure is anchored at the seabed and kept taut by a system of buoys at the top. The tower floor, a 8 m long structure, is connected to the next ones with four ropes such that each floor is perpendicular to its vertical neighbours. The floors are vertically spaced by 40 m, with the lowermost one located 100 m above the sea bottom [11]. Each floor supports four Optical Modules (OMs), two at each end, one down-looking and one looking horizontally. An OM is composed by a photo-multiplier tube (PMT) enclosed in a 13″ pressure-resistant glass sphere [12]. The PMT is a 10" Hamamatsu[1] R7081Sel with 10 dynode stages. A Front-End Module board (FEM) is also placed inside the OM. It applies a quasi-logarithmic compression on the analog signal, which is then sampled at 200 MHz by means of two 100 MHz Flash ADCs, staggered by 5 ns [13].

[1] Hamamatsu Photonics, 812 joko-cho, Hamamatsu city, 431-31 Japan, web-site: `www.hamamatsu.com`

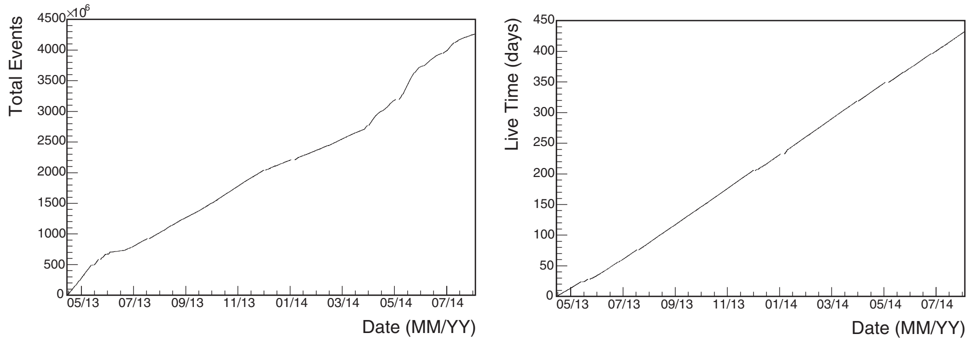

Figure 1. Cumulative number of triggered events and the corresponding live time as a function of time.

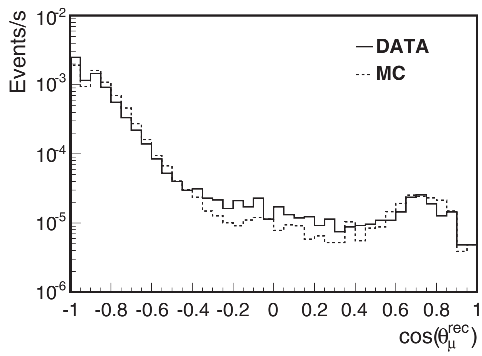

Figure 2. Zenith angular distributions of reconstructed atmospheric muon tracks. Solid histogram is data, dashed histogram is Monte Carlo simulation.

3. Muon data taking

The presence of an optical background, due to ^{40}K decays and bioluminescence, gives an average rate of about 50 kHz of uncorrelated single photo-electron signals on each PMT [14]. An on-line muon selection algorithm is used to reduce the amount of PMT data due to the optical background. This algorithm is based on searching *trigger seeds* among the PMT signals (*hits*), such as Simple Coincidences (SCs): coincidences within 20 ns between two hits occurring on two PMTs located at the same extremity of a given floor; Floor Coincidences (FCs): coincidences within 100 ns between two hits recorded at the opposite ends of the same floor; Charge Shootings (CSs): hits exceeding a charge threshold of about 10 p.e. [15]. The cumulative number of triggered events and the correspond live time as a function of time are plotted in Fig. 1.

4. Muon depth intensity relation

Muon data recorded between April 2013 and August 2014 were analysed [16]. A total of 606,546 atmospheric muon tracks were reconstructed during 411.1 days of live time. The zenith-angle distribution of reconstructed events and its comparison with Monte Carlo simulations are shown in Fig. 2. The true number of muon events $N_\mu(\theta_\mu)$ as a function of zenith-angle is obtained applying an unfolding procedure on the reconstructed angular

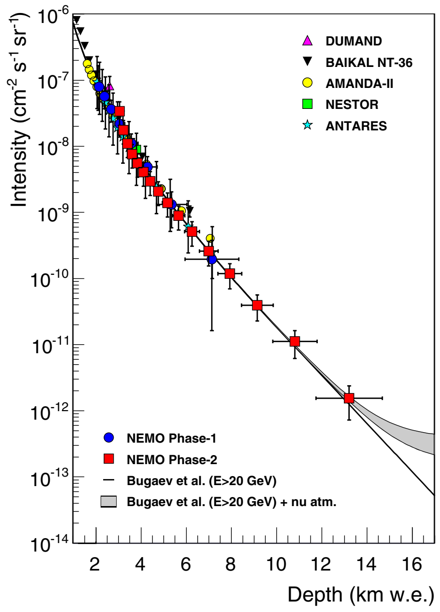

Figure 3. Vertical muon intensity, $I(\theta_Z = 0, h)$, versus depth measured with the NEMO Phase-2 tower [16]. For comparison, results from other experiments are shown: DUMAND [22], BAIKAL [23], NESTOR [24], AMANDA [25], ANTARES [26] and NEMO Phase-1 [10]. The solid line is the prediction of Bugaev et al. [27]. The shaded area at large depths includes atmospheric neutrino-induced muons. Error bars include statistical and systematic uncertainties.

distribution. The muon intensity $I(\theta_\mu)$ is then calculated using the relation

$$I(\theta_\mu) = \frac{N_\mu(\theta_\mu) \cdot m(\theta_\mu)}{A_{eff}(\theta_\mu) \cdot T \cdot d\Omega}, \tag{1}$$

where $m(\theta_\mu)$ and $A_{eff}(\theta_\mu)$ are respectively the average muon multiplicity and the detector effective area as determined from the Monte Carlo simulations; T is the detector live time corresponding to the selected data sample and $d\Omega$ is the detection solid angle.

The final step of the analysis was the evaluation of the Depth Intensity Relation (DIR). The DIR describes the vertical muon flux intensity as a function of the muon slant. An atmospheric muon, reaching the detector located at a vertical depth D from a zenith angle $\theta_Z = 180^\circ - \theta_\mu$, propagates through a water slant depth $h = D/\cos\theta_Z$. The measured flux $I(\theta_\mu)$ was therefore transformed into the DIR using:

$$I(\theta_Z = 0, h) = I(\theta_Z) \cdot \cos(\theta_Z) \cdot c_{corr}(\theta_Z), \tag{2}$$

where the term $c_{corr}(\theta_Z)$ is a geometrical correction factor which takes into account the curvature of the Earth [21]. Results are plotted in Fig. 3. For details about the analysis and discussion on results see [16].

5. Conclusions

The NEMO Collaboration has achieved a major milestone with the installation and operation of a tower-like prototype at 3500 m depth. The NEMO Phase-2 tower, composed by 8 floors for a total height of 380 m, equipped with 32 PMTs, was deployed in 2013 about 80 km offshore Capo Passero (Italy). It was continuously operated for more than one year.

Atmospheric muon tracks have been reconstructed and their measured angular distribution has been compared with Monte Carlo simulations. The muon depth intensity relation has been evaluated and compared with previous data and predictions, showing a good agreement. With the present analysis, the muon depth intensity relation has been measured in water for the first time up to an equivalent depth of 13 km.

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