Capabilities of an Underwater Detector as a Neutrino Telescope and for the Neutrino Oscillation Search

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Abstract

We report on the results of a Monte Carlo simulation study of a km^3 scale deep underwater Cherenkov detector aimed at detecting neutrinos of astrophysical origin. This analysis has been undertaken as part of the NEMO R&D project to develop such an experiment close to the Southern Italian coasts. We have studied the reconstruction capabilities of various arrays of phototubes in order to determine the detector geometries which optimize performance and cost. We have also investigated the possibility of designing a detector with characteristics suited to an experiment on atmospheric neutrino oscillations.

1   A km^3 Detector for Neutrino Astronomy:

The discovery of high energy neutrinos ($E_\nu > 100$ MeV) of astrophysical origin would open the ν-astronomy field complementary to the well established γ-ray astronomy one. Neutrinos are subject to less absorption than photons and therefore can bring information on the deep interior of sources. The observation of tens of TeV γ-ray emitters (Thompson et al., 1995, Krennrich et al., 1998) reinforces the possibility of existence of "beam dump sources", accelerated proton beams interacting with gas of matter or photons. Neutrino production is expected from $\pi^\pm$ decay in analogy with photons arising from π^0 decay. Among the possible sources are active galactic nuclei (AGNs) made of a black hole and a surrounding accretion disk, binaries where a non compact companion transfers mass to the compact one (neutron star or black hole) with consequent development of an accretion disk, supernova remnants in which particles interact in the acceleration region and γ-ray bursts where a fraction of the kinetic energy of a relativistic fireball is converted by photo-meson production into neutrinos. Gaisser, Halzen & Stanev, 1995, estimate rates of about 3 upwardgoing ν-induced muons/yr and 0.1-25 muons/yr with $E_\mu > 1$ TeV in a 0.1 km^2 detector from galactic and extragalactic sources, respectively. These estimates are based on existing limits from air shower experiments on γ emissions in the 100 TeV energy range and on the assumption that ν fluxes are expected to be comparable to γ-ray ones, except for γ absorption. Diffuse fluxes from AGNs may vary of orders of magnitude according to different models. The signal from ν sources is expected to dominate the atmospheric ν background at energies $\gtrsim 10$ TeV, since the differential spectral index of high energy atmospheric neutrinos ($\gamma \sim 3.7$) is larger than that expected for ν cosmic accelerators ($\gamma \sim 2 - 2.5$). Given the predicted low fluxes, the required sensitivity calls for km^3 scale ν telescopes, with the ability to measure the energy and direction of ν-induced muons, in order to reject the atmospheric neutrino background.
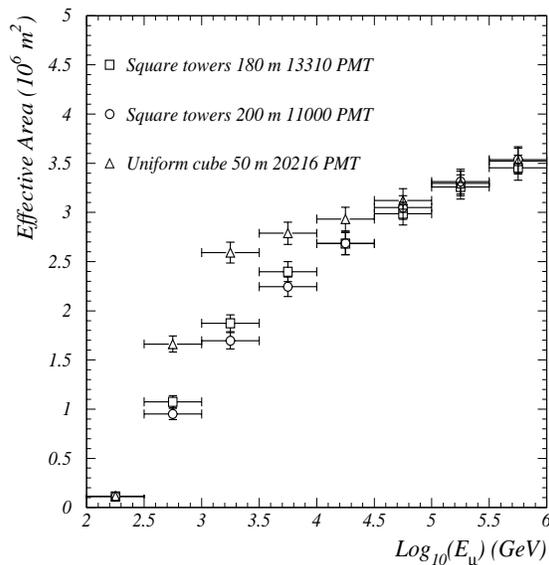
Figure 1: Effective area vs muon energy for 3 PMT arrays: a parallelepiped with distance between PMTs of 50 m; 2 square tower configurations with distance between centers of towers of 180 m and 200 m and between PMTs in each tower of 30 m. Total numbers of PMTs are indicated for each array. The error bars are due to the Monte Carlo statistics.

Underwater Cherenkov arrays of phototubes (PMTs) can satisfy these requirements and can be developed at depths of the order of 3000 m where the atmospheric muon background is reduced with respect to surface by a factor of $\sim 10^{-6}$.

NEMO (NEutrino subMarine Observatory) is an R&D project of the Italian INFN for a ν telescope to be deployed in the Mediterranean Sea near the Southern Italian coasts, where transparency and other water parameters are optimal (Capone et al., 1999). We have investigated the response of various arrays of photo-tubes using a "fast" Monte Carlo simulation of Cherenkov light emission by high energy muons and of the detector response. The speed of the simulation is an important feature at this stage of the feasibility study because it allows us to easily change various inputs, such as the geometry of the array, the PMT character-istics and the kinematics of the events. Moreover, it allows a fast propagation of muons above 10 TeV to be performed. The main limit of this code is that it transports muons but not hadronic or electromagnetic show-ers. We will perform more accurate studies with a full GEANT-based (Brun et al., 1987) simulation that we are developing (Bottai, 1998), once the structure of the detector is well defined. The total energy loss due to Cherenkov emission is orders of magnitude less important than the total ionization for relativistic muons, but it has the relevant feature that all photons are emitted at $\Theta_c \sim 41.2°$ around the μ trajectory. The simulation uses parameterizations to describe the energy losses of muons by ionization and by stochastic processes (pair production, bremsstrahlung and nuclear interactions). The Cherenkov light emitted by electromagnetic show-ers is produced according to the parameterization in Belyaev et al., 1979. Light is attenuated as the result of absorption, which affects the amplitude of signals, and of scattering, which affects both the signal amplitude and the time of arrival with consequent difficulties in track reconstruction. In the simulation, an attenuation length of light of 55 m has been assumed, as due to absorption only. Scattering of light is not simulated, but this is a reasonable approximation since measurements of the scattering length show that it is $\gtrsim 70$ m in the Mediterranean sea and the fraction of backscattered light is quite small. We have simulated optical modules (OMs) made of couples of typical byalcali PMTs looking one upward and the other downward, with a pho-tocadode diameter of 15 inch, time resolution of 2.5 ns and quantum efficiency of 0.25. We have assumed a detection threshold of 0.25 photoelectrons (PE). The events are assumed to give a trigger if they hit at least 5 PMTs. The reconstruction of events requires in fact the determination of 5 parameters (the zenith and azimuth angles and the coordinates of the "pseudo-vertex", i.e. the position of the particle when the light hits the first PMT). We perform it by means of a minimization procedure of the χ^2 between expected and measured arrival times of photons. We are studying how the charge information can be used.

In order to minimize the cost of km^3-size detectors, a structure made of towers of strings of PMTs can be a better solution than uniformly spaced arrays. We have assumed 300 m high arrays. Since we are interested in determining the response of the detector to high energy ν-induced muons produced by astrophysical sources, we consider a relevant parameter the effective area (the area including the reconstruction efficiency) as a function of energy for muons coming from outside the "horizon" of the detector, i.e. a closed surface which contains the detector at a distance of 2 attenuation lengths. In Fig. 1 we compare the effective areas of a cubic array of 50 m spaced PMTs (20,216 PMTs) with 2 arrays made of square towers with their centers separated by 180 m and 200 m (13,310 and 11,000 PMTs, respectively). The square towers are made of 5 strings, 4 of which are located at the vertices and at a distance of 15 m from the one in the centre. The PMTs are vertically spaced by 30 m. It turns out from Fig. 1 that the areas of the detectors are comparable; nevertheless the uniform array performs better in track reconstruction.

2 Neutrino Oscillations in an Underwater Detector:

We have investigated the capabilities of an underwater array of determining the oscillation parameters in the region suggested by current atmospheric ν experiments (Ambrosio et al., 1998; Fukuda et al., 1998), which in the $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillation scenario is maximum mixing and $\Delta m^2 \sim 3 \cdot 10^{-3}$ eV^2. The oscillation probability is a function of the ratio of the baseline L and of the neutrino energy E_ν. Atmospheric neutrinos offer the possibility to explore a wide range in L/E_ν due to the variation of the baseline with the zenith angle

θ between $L \sim 20$ km for downward-going neutrinos and $L \sim 2R_\oplus \sim 12800$ km for upward-going neutrinos. Hence sensitivities to $\Delta m^2 \sim 10^{-4}$ eV^2 can be achieved. The measurement of the number of upward to downward events as a function of the ratio of the baseline to the energy, $N_{up}(L/E_\nu)/N_{down}(L'/E_\nu)$, with $L' = L(\pi - \theta)$, can provide the modulated pattern of the survival oscillation probability (Curioni et al., 1998). On the other hand, if neutrinos do not oscillate the ratio is expected to be 1 due to the up-down symmetry of ν fluxes above a few GeV. The possibility to measure downward-going events allows the normalization of calculations to a "reference" flux not affected by oscillations. As a matter of fact, if $E_\nu \sim 1$ GeV and $\Delta m^2 \lesssim 10^{-2}$ eV^2, downward neutrinos are not affected by oscillations, while upward neutrinos are reduced since L/E_ν ranges up to 10^4 km/GeV.

An underwater Cherenkov detector can provide indications of the neutrino direction and energy through the measurement of the induced muons. The muon energy can be derived from the range of almost vertical muons which do not leave the array (Moscoso et al., 1998). We have defined the following variable to represent the vertical muon range: the maximum difference of the heights of the highest and lowest hit PMTs $(z_{max} - z_{min})_{max}$ among those calculated on each string. In the following we will assume that no information is obtained from the hadronic part of the ν charged current (CC) interaction due to the insufficient granularity of the detector. In this approximation, a smearing will result in the oscillation pattern due to the angle between the muon and the neutrino ($\langle \Theta_{\nu\mu} \rangle = 6°$ for the selected sample of this analysis) and to the energy transferred to the hadronic products. Nevertheless, we will show that the oscillation pattern can be significant enough to discriminate the no-oscillation hypothesis and to have some indication on the Δm^2 value. After studying various configurations of dense arrays of PMTs we have chosen the following configuration which reconstructs best tracks in the vertical region: 7 strings, with 1 in the center and 6 at the vertices of a hexagon of 15 m side. OMs are made of 2 PMTs looking upward and downward and they are vertically spaced by 3 m; the strings are shifted in the vertical direction with respect to one another by 1 m, in such a way that PMTs do not lie in the same horizontal planes. The total number of PMTs is 1414. We find that increasing the vertical distance between OMs causes a dramatic decrease in the statistics of events satisfying the requirements of the analysis ($\sim 40\%$ for 6 m). Since PMT arrays do not have a volume determined by active elements, we have generated 20.4 million events in a much larger volume than the tower dimensions (a cylinder of 72 m radius and 418 m high). We find that the effective volume of this tower of strings is about constant for $E_\mu \gtrsim 2$ GeV and its value is $2 \cdot 10^6$ m^3. Atmospheric ν interactions have been simulated by means of the NUIN generator (Lipari et al., 1995) for $E_\nu \geq 1$ GeV with statistics corresponding to 34.4 yr of running time. We have used the Bartol group ν flux, including recent calculations of geomagnetic cut-offs (Gaisser et al., 1988). The generator provides the kinematics of ν-CC interactions for all flavors with particular attention to the processes which dominate at low energies (i.e. quasi-elastic scattering and 1 π production). We have used the parton structure functions GRV(94) (Glück, Reya & Vogt, 1995) for deep inelastic scattering. ν_e induced interactions have not yet been considered. We have neglected the following sources of noise: β-decay of ^{40}K and consequent light emission by electrons with a rate of the order of 50 kHz at the level of 1 PE signals (this background should not represent a problem due to the requirement of coincident measurement of 5 PMTs and to the applied filter that requires that the coincidence happens in a time window compatible with light propagation); bioluminescence bursts due to living organisms; high energy atmospheric muons whose vertical intensity at 3000 m depth is $\sim 10^{-8}$ cm^{-2} s^{-1} sr^{-1}. The sample of events is selected by requiring $|\cos\theta| > 0.94$, at least 1 PMT hit on each string (this cut notably improves the quality of reconstruction), by imposing some containment cuts (-135 m $< z_{min} < z_{max} <$ 135 m, the x and y coordinates of the reconstructed vertex being inside a circle of radius 70 m and by requiring -135 m $< |z| <$ 135 m) and $(z_{max} - z_{min})_{max} >$ 18 m. The surviving events are 750 yr^{-1} for no-oscillations. The angular separation $\Delta\Omega$ between the simulated and reconstructed μs is distributed with average angle of $3°$ and RMS of $6.6°$. Only 1% of the selected events are badly reconstructed with $\Delta\Omega > 20°$. In Fig. 2(a) we show $(z_{max} - z_{min})_{max}$ vs the simulated μ energy. The superimposed points forming a line show the "true" range of the μs. We are working on an analytical correction to take into account the μ track small angle with respect to the vertical in order to improve the energy resolution of the detector (i.e.

the width of the distribution around the "true" range). First estimates of the background due to atmospheric μs indicate that even considering 6 planes of anticoincidence at the top of the tower it may be necessary to reduce the fiducial volume of the detector. Better reconstruction algorithms may also help. This requires the inclusion of the hadronic part of the interaction. Even if preliminary, the results of this work are shown in Fig. 2(b) which represents the upward/downward muon ratio as a function of $(z_{max} - z_{min})_{max}$ for 5.7 yr of the tower running. As can be seen, the dips of the curves obtained for $\Delta m^2 = 1 \cdot 10^{-3}, 2.5 \cdot 10^{-3}$ eV^2 are representative of the minima in the oscillation survival probability, while for $\Delta m^2 = 5 \cdot 10^{-2}$ eV^2 the resolution of the experiment is such that the fast oscillations are averaged at 1/2. Even if the tracking efficiency can be improved, more than 1 tower may be needed in order to reach competitive statistics for this kind of experiment.
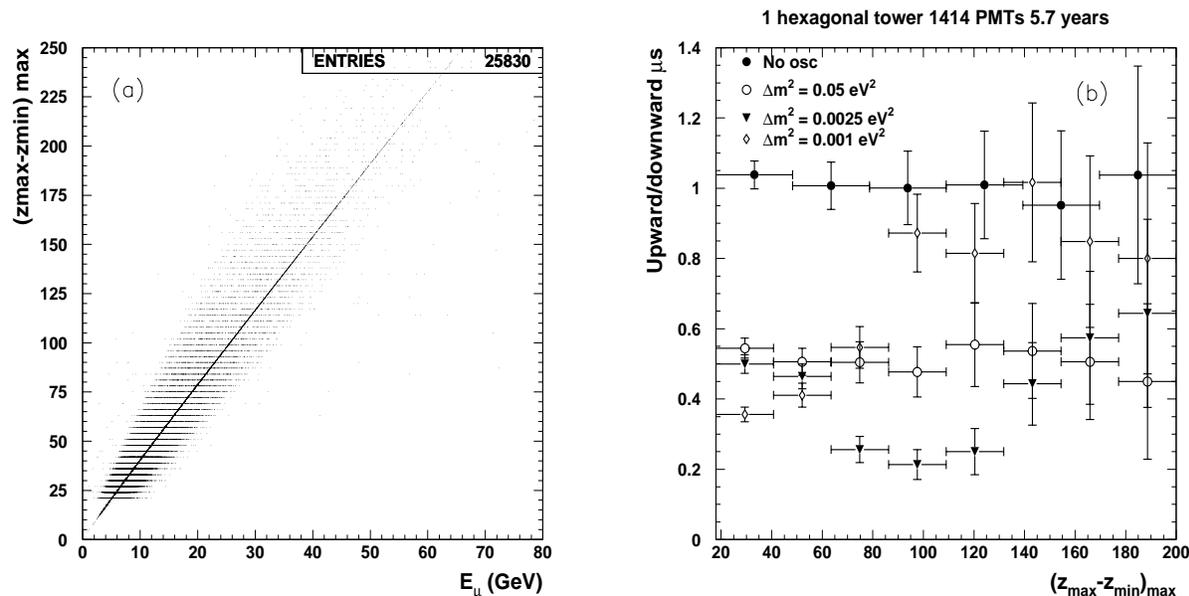
Figure 2: (a) Correlation between $(z_{max} - z_{min})_{max}$ and the simulated energy of almost vertical muons. The points forming a line represent the "true" range of simulated μs. (b) Upward/downward muon ratio vs $(z_{max} - z_{min})_{max}$ for the no-oscillation case and $\Delta m^2 = 1 \cdot 10^{-3}, 2.5 \cdot 10^{-3}, 5 \cdot 10^{-2}$ eV^2.

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