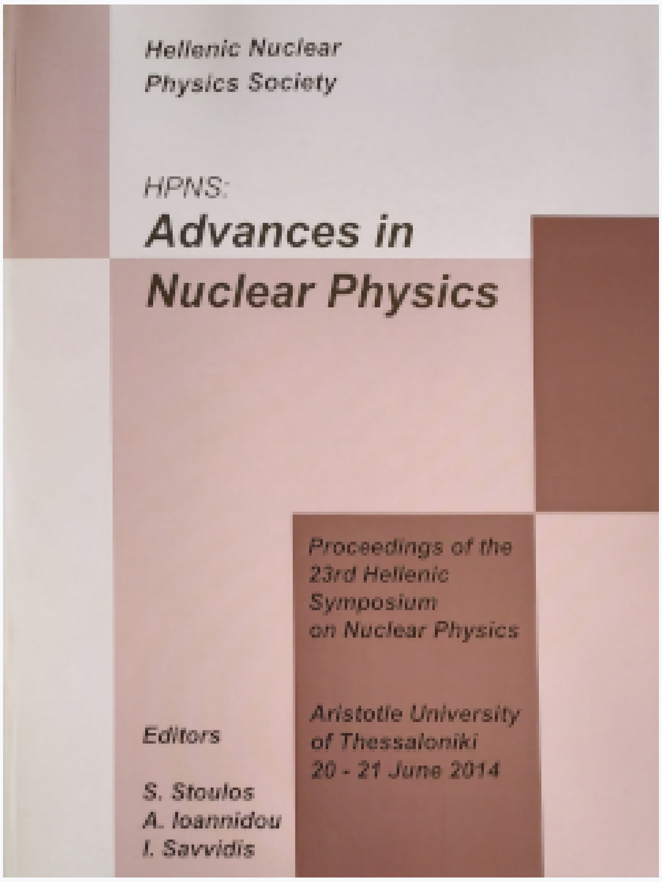
HNPS Advances in Nuclear Physics

Vol 22 (2014)

HNPS2014



The response of an autonomous underwater telescope to high energy neutrinos for the observation of Gamma-ray bursts (GRBs)

K. Balasi, C. Markou, K. Tzamarioudaki, P. Rapidis, E. Drakopoulou, K. Pikounis, C. Begatelas

doi: 10.12681/hnps.1936

The response of an autonomous underwater telescope to high energy neutrinos for the observation of Gamma-ray bursts (GRBs)

Konstantia Balasi[1], Christos Markou[1], Katerina Tzamarioudaki[1], Petros Rapidis[1], Evangelia Drakopoulou[1], Konstantinos Pikounis[1], Christos Bagatelas,

[1]*Institute of Nuclear and Particle Physics, NCSR "Demokritos", Patriarxou Grigoriou & Neapoleos, 15310 Aghia Paraskevi, Athens, Greece.*

Abstract

The response of an underwater neutrino detector is discussed for investigating its performance to the detection of muons and high energy neutrinos. The afformentioned telescope consists of an autonomous battery operated detector string to a central 4-floor tower. In this aim, we utilised a fast detector simulation program, SIRENE, to simulate the hits from Cherenkov photons at ultra high energies (as high as 10^{20} eV). In order to optimize the detector, analytical studies for different configurations and characteristics of the photo-multiplier tubes inside the optical modules of the telescope was also examined.

INTRODUCTION

The GRBNeT project has as its objective the deployment of a neutrino telescope for detecting high energy neutrinos emitted by Gamma Ray Bursts (GRBs). The deployment site is a deep part of the Mediterranean Sea, an area that includes its deepest point. The site is located in the open sea off the southeaster tip of the Peloponnese in the vicinity of the town of Pylos. One of the extremely desirable features of this region of the Mediterranean Sea is the existence of four sizeable plateaus at depths ranging from 3000 to 5200m that can accommodate a neutrino telescope. Thus, the closest site at 13 km from the nearest landfall and 3000 m depth allows for convenient deployment and can be used for tests, while the area at 48 km and at a depth of 5200 m allows for the deployment of a detector with reduced background from the downgoing muons from cosmic rays and higher sensitivity to very high energy neutrinos.

NEUTRINO PRODUCTION

The conventional models for neutrino production are based on interactions of accelerated protons and nuclei with photon or matter fields near or in the astrophysical source. The primary reaction produces neutral and charged pions

$$p + p/\gamma \rightarrow \pi^{+} + \pi^{-} + \pi^{0} + X.$$

Whereas neutral pions mainly decay into photons, which can subsequently be detected by imaging air-shower cherenkov telescopes, charged pion decays yield neutrinos.

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \nu_{\mu} + \nu_{\mu}$$

$$\pi^{-} \rightarrow \mu^{-} + \nu_{\mu} \rightarrow e^{-} + \nu_{e} + \nu_{\mu} + \nu_{\mu}$$

$$\pi^{0} \rightarrow 2\gamma$$

In these decays, the fraction of energy carried by the resulting neutrinos is approximately independent from the mesons' energies. The neutrino spectrum thus closely resembles the proton spectrum.

GAMMA RAY BURSTS (GRBs)

Gamma Ray Bursts (GRBs) are short-duration emissions of γ-rays associated with extremely violent explosions in the Universe in distant galaxies. These are characterized by the largest luminous energy emissions known to us up to now. The first observations of GRBs happened in the 1960s by the American satellites VELA, which were designed to detect clandestine atmospheric nuclear weapons tests. In 1973, Klebesabel et al. [1] of the Los Alamos Laboratory published the first interpretation for the cosmic origin of GRBs excluding sources in the Solar system. In the same publication, the time duration of the burst and the distribution of γ-rays were presented for the first time. Important developments on the understanding of GRBs occurred in 1997 with the detection of x-rays and the measurement of the optical spectrum redshift [2]. These measurements placed the stars. Today, satellite and earth-bound instruments detect at least one GRB each day. The data from these observations are collected and compiled by the Gamma Ray Burst Coordination Network in the Goddard Space Flight Center of NASA. GRBs can be classified on the basis of the time profile of the burst as:

- Short burst when their time duration is less than 2 secs,
- Long burst when they last for more than 2 secs.

Most GRBs are long burst ones, and they have been studied in more detail. These usually exhibit a long tail, the ‘afterglow’. Current studies suggest that these GRBs are associated with the death of high mass stars in star forming galaxies. In many cases, long burst GRBs are associated with core-collapse supernovae. The short burst GRBs occur in regions without indications of star formation, and star death as their source is, therefore, excluded. Their redshift is, in general, smaller than the long burst GRBs and the merger of binary systems of two neutron stars has been suggested as the most possible origin of those.

NEUTRINO TELESCOPES

Because of their very low interaction cross-section and their lack of charge, neutrinos can not be detected directly. However, the products of a neutrino interacting with a nucleon of the surrounding matter can be detected. Neutrino telescopes use the Cherenkov light emitted by muons (and other charged particles) to reconstruct these particle’s tracks. At high energies, due to the kinematics of the interaction, a muon track will point in approximately the same direction as the original neutrino. This eventually allows to reconstruct the astronomical position of a potential neutrino source.
Neutrinos are weakly interacting, so the only available interaction channels are via exchange of $W\pm$ or Z vector bosons, i.e. via charged current (CC) or neutral current (NC) reactions, respectively. In neutrino telescopes, the interactions will always occur with nucleons of the surrounding matter, usually water or rock. Due to flavour and charge conservation, the products of CC interactions depend on the flavour of the initial neutrino. The charged lepton’s flavour in the final state will always be the same as the initial neutrino’s flavour. So a $\nu\mu$ will yield a $\mu-$, an interacting νe will produce an electron and a $\nu\tau$ will produce a $\tau-$. This is of course also true for the respective anti-particles. In general, CC interactions can be written as

$$\nu_f + X \rightarrow f^{\pm} + X^{'}$$

where f denotes the neutrino flavour and X stands for an arbitrary nucleon [3, 4, 5, 6]. The final state of this reaction includes the charged lepton and a hadronic part X which will immediately lead to a particle cascade localised at the interaction vertex. Figure 1 Shows (pseudo-)Feynman diagrams for these interactions.

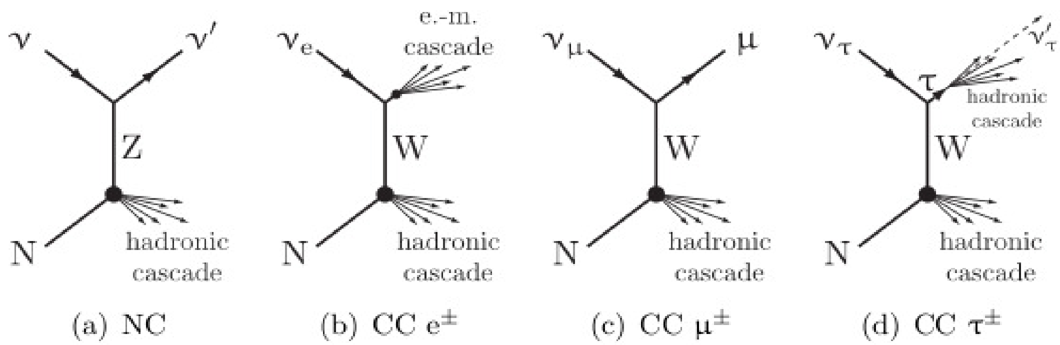


Figure 1 Feynman diagrams for neutrino-nucleus interactions.

RESULTS

Our aim is to detect high energy neutrinos from GRBs and therefore the acceptance threshold for each optical module must be tuned appropriately to guarantee a significant suppression of the background from radioactive decays of ^{40}K in the sea water. A higher acceptance threshold for the optical modules also helps to reduce the background from atmospheric muons which are produced by particle showers in the atmosphere and have a softer energy spectrum than the signal muons. By deploying the autonomous string at a large sea water depth a significant reduction of the atmospheric muon background is provided naturally since muons need to have high enough energy to penetrate at the depth considered. The higher acceptance threshold of the optical modules works on the same direction, providing an additional suppression factor for the atmospheric muon background.

We have performed detailed studies on the rejection of the atmospheric muon background. For this, atmospheric muon bundles have been generated using the MUPAGE program [7]. The Monte-Carlo program MMC has been used for the muon propagation [8]**.** Another source of background comes from atmospheric neutrinos which are produced by the interaction of cosmic rays with the molecules of the atmosphere. The energy spectrum of the atmospheric neutrinos is softer than that expected for neutrinos from GRBs, so by requiring high muon (or neutrino) energy the contribution of atmospheric neutrinos is reduced significantly [9]. For a full size detector, the requirement of a time coincidence of the neutrino signal from GRBs with the satellite or terrestrial telescope observation of GRBs (a GRB alert) will give a drastic reduction of the atmospheric neutrino contribution. The autonomous detection unit should have the ability to trigger events (first level trigger) using local coincidences (optical modules on the same floor) and to use coincidences between floors for further filtering of the events. For this reason, simulation studies for the optimization of the geometry of the autonomous detection unit have been performed and they have shown that a string with 4 floors, each floor equipped with 4 optical modules, is a configuration that can achieve the adequate reduction of the atmospheric muon background in order to give a reasonable rate of triggered events. In the following, we will concentrate on this geometrical configuration for the autonomous string, with a distance of 30 m between floors and the 4 optical modules of a floor being on a square of 5.5 m distance (Figure 2). The information of the 4 optical modules on the same floor will be used for first level triggering. If a trigger is set, then the information from all optical modules is kept.

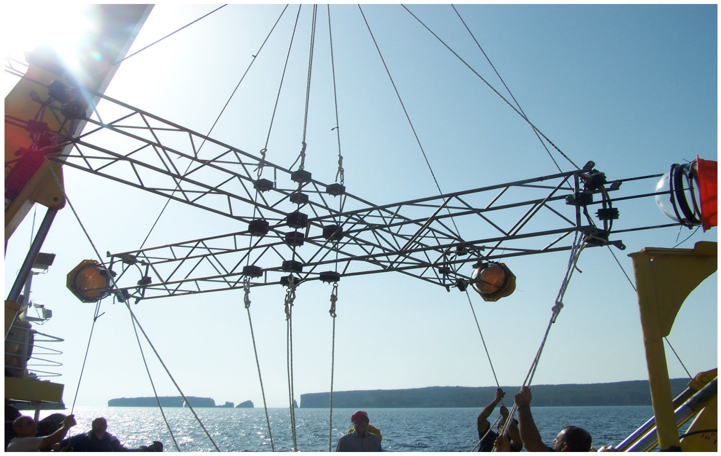


Figure 2 A neutrino detector with 4 photomultipliers used in a test deployent at Pylos, Messinia, on October 2015.

The contribution of the atmospheric muon background has been studied by generating atmospheric muon bundles using the MUPAGE program and simulated taking also the contribution of noise due to 40K decays into account. As mentioned before, the number of atmospheric muons is orders of magnitude higher than muons coming from neutrinos, so it is common practice to simulate atmospheric muons corresponding to a live-time of several hours and then to extrapolate to the desired live-time. At a depth of 3500 m muons of energy lower than 100 GeV are not expected to contribute to the rate. Applying the requirement of 3 photons in an OM gives a strong reduction of the number of background events as can be seen in Fig. 3. This threshold also provides a strong suppression of the noise due to 40K decays. The numbers of events expected from atmospheric muons, taking also the noise contribution into account, during 24 hours of operation are given in Table 1. The suppression achieved by increasing the acceptance threshold of the OMs is also given in Table 2. We have also examined the condition of having 4 and 5 optical modules on different floors with 3 and 5 photons, respectively. Our results are shown in Table 3.

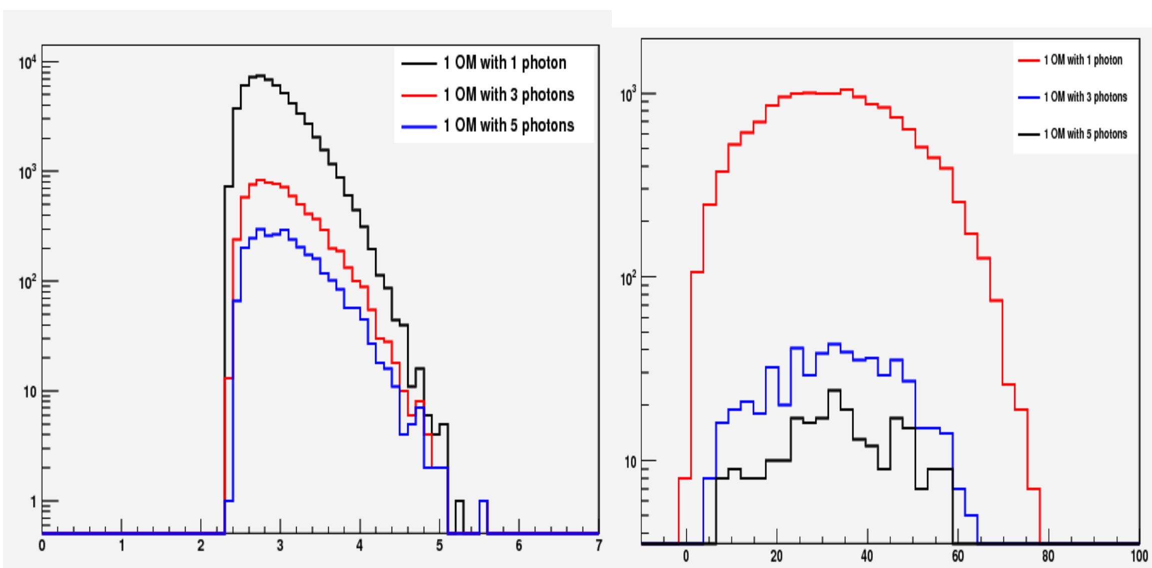


Figure 3. The spectrum of the bundle energy (logE) and the zenith angle of atmospheric muons with E > 100 GeV are shown for all events with at least 1 OM with the acceptance threshold set to 1 photon (black line), with at least 1 OM with 3 photons (red line) and with at least one OM with 5 photons (blue line).

Table1. The numbers of events expected from atmospheric muons, taking also the noise contribution into account, during 24 hours of operation are given. The ratio of events surviving a higher acceptance threshold for the OMs is also shown.

condition	muons/day
at least 1 OM with 1 photon	2816
at least 1 OM with 3 photons	579
at least 1 OM with 5 photon s	200

Table 2. The numbers of events expected from atmospheric muons, taking also the noise contribution into account, during 24 hours of operation are given.

condition	muons/day
at least 1 OM with 1 photon	1239
at least 2 OMs with 3 photons on the same floor	271
at least 3 OMs with 3 photons on the same floor	97

Table 3. The numbers of events expected from atmospheric muons for 1 day of operation, when we demand 4 and 5 optical modules on different floors having 3 and 5 photons, respectively.

condition	muons/day
at least 4 OMs with 3 photons on the different floors	113
at least 4 OMs with 5 photons on the different floors	61
at least 5 OMs with 3 photons on different floors	26
at least 45 OMs with 3 photons on different floors	10

Figure 3. Test deployment on October 2015 for the GRBNeT neutrino telescope.

SUMMARY AND CONCLUSIONS

Neutrino events have been generated with an E^{-1} energy spectrum using the ANIS program. For this study the simulation for the detector response is very demanding on computing power. This is expected, as we aim to have a very large instrumented area with detection units widely separated from each other. For this reason we have decided to import the SIRENE package that has been recently developed to perform a fast simulation of the detector response using PDFs.

The contribution of the atmospheric muon background has been studied by generating atmospheric muon bundles using the MUPAGE program and simulated taking also the contribution of noise due to ^{40}K decays into account. At a depth of 3500 m muons of energy lower than 100 GeV are not expected to contribute to the rate. Applying the requirement of 3 photons in an OM gives a strong reduction of the number of background events. This threshold also provides a strong suppression of the noise due to ^{40}K decays. By increasing the acceptance threshold of the OMs a good suppression is achieved. We have also examined the condition of having 4 and 5 optical modules on different floors with 3 and 5 photons, respectively. We again conclude that the background can be suppressed when we increase the acceptance threshold.

ACKNOWLEDGMENTS

This research was supported by the THALIS project of the General Secretariat for Research and Technology of the Hellenic Ministry of Development.

REFERENCES

1. Astrophysical Journal, vol. 182, p.L85.
2. Nature 387, 783-785, 19 June 1997.
3. K.G. Balasi, T.S. Kosmas, P.C. Divari and V.Ch. Chasioti, AIP Conf. Proc. 972 (2008) 554.
4. K.G. Balasi, T.S. Kosmas, P.C. Divari and H.Ejiri, J. Phys. Conf. Ser. 203 (2010) 012101.
5. K.G. Balasi, T.S. Kosmas, P.C. Divari, AIP Conf. Proc. 1180 (2009) 1.
6. K.G. Balasi, T.S. Kosmas, P.C. Divari, Prog. Part. Nucl. Phys. 64 (2010) 414.
7. Nuclear Instruments and Methods A 567, 492, 2006.
8. D. Chirkin, W. Rhode, hep-ph/0407075v1, 2004.
9. Phys. Rev. D38 (2003) 083001.