Study of atmospheric neutrino oscillations in ANTARES

C. Cârloganu[a]
On behalf of the ANTARES collaboration

[a]NIKHEF,
Kruislaan 409 , 1098 SJ Amsterdam, The Netherlands

The potential of the ANTARES 0.1 km^2 detector for the study of the atmospheric neutrino oscillations is discussed.

1. Introduction

The importance of atmospheric neutrinos for the study of neutrino oscillations has been stressed in the literature [1]. Upgoing neutrinos have baseline lengths up to the diameter of the Earth and a large energy spread, allowing, in principle, tests of a wide range of mixing parameters.

SuperKamiokande and, more recently, MACRO have published evidence for two family neutrino oscillations, $\nu_\mu \leftrightarrow \nu_\tau$, with the most probable values of the mixing parameters $\Delta m^2 = 3.5 \cdot 10^{-3}$eV^2 and $\sin^2 2\theta$=1 [2]. In this scenario, an atmospheric neutrino experiment sensitive to neutrino energies between 10 and 60 GeV could observe both the disappearance and the regeneration of muon neutrinos crossing the Earth. Other than providing a convincing proof of oscillations, such a complete observation of the oscillation pattern would allow a precise and independent measurement of the mixing parameters.

The ANTARES collaboration has investigated the possibility of studying neutrino oscillations with its proposed 0.1 km^2 detector [3,4]. The results are reported here.

2. Detector simulation and performance

The ANTARES 0.1 km^2 detector has been described in detail [5]. The simulations performed in order to characterise the detector performance include the present knowledge of the detector environment and characteristics. Measurements performed *in situ* [6] quantified the deep-sea optical background and showed that absorption ($\lambda_{\rm abs} \sim 55$ m at 470 nm) dominates largely diffusion in the sea water. We expect that the timing resolution of the ANTARES detector will be dominated by the photomultipliers (PMT), with a typical transit time spread $\sigma_{\rm TTS}$ of 1.3 ns. Tests and simulations show indeed that the PMTs can be positioned relative to each other to within 20 cm and their relative timing calibration can be performed with an accuracy better than 0.5 ns.

In the low energy region ($E_\nu \leq 300$ GeV), almost all the events seen in the detector originate from neutrino interactions in the instrumented volume or in its close vicinity (contained events). Light from both the muon and the hadronic jet produced in the neutrino interaction is detected. Only the reconstruction of the muon is considered for the moment, although efforts are going on in order to also reconstruct the hadronic shower. The muon reconstruction technique and its performance will be detailed below.

2.1. Muon reconstruction

The muon trajectory is reconstructed by maximisation of a likelihood function based on the time and spatial information of the PMT hits.

The detector sampling is much better in the vertical direction than in the horizontal plane: the distance between two adjacent PMT storeys along the detector strings is 12 m, whereas the minimal distance between strings is about 60 m. This leads to two distinct topologies in the detected events: muons with energies as low as 10 GeV can be detected provided that they are close enough to one string and sufficiently vertical; higher energy muons can give signals in several strings. Naturally, the multi-string events are much better reconstructed than the single-string events: half of them have an error on the muon zenith angle of less than $0.3°$, compared to $1.6°$ in the case of the single-string events.

The muon energy is inferred from the measured muon range. Events that are at least partially contained within the detector volume are selected. For the single-string events, containment is ensured by requiring the reconstructed muon track to have a zenith angle within $30°$ of the vertical and requiring the highest and lowest storeys not to have fired in the event.

A special track containment estimator is used for the multi-string events. After reconstruction, the starting and stopping points of the track are located. Then the track is extrapolated backwards and forwards to see if any PMTs could have seen the track before the starting point or after the stopping point. If not, the track is clearly non-contained. The containment estimator is the sum of the amplitudes of the hits that would have been seen on these optical modules if the track were not contained.

The energy of the muon is taken as the visible energy in the detector, with corrections applied to it in the case of the partially contained events. Globally, the muon energy resolution is better than 30% for (partially) contained muons with energies higher than 20 GeV.

2.2. Background rejection

The oscillation signal consists of upgoing, contained muon neutrinos. Two main categories of background were considered: first, non-contained muons (upgoing or downgoing) which are reconstructed as contained upgoing events; second, truly contained events that were produced by electron neutrinos.

For the latter case, three years of data were simulated and no fake events were seen after reconstruction and selections. In addition, no fake events were recorded for the first category of background, but in this case the situation is more complicated due to the contribution of downgoing atmospheric muons. Their flux is very high and only a limited data set was available (~4 days for the multi-muon events). Efforts are under way to increase the statistics.

3. Study of atmospheric neutrino oscillations

The number of signal events was calculated using the Bartol parametrisation [7] for the flux of atmospheric neutrinos and the expected experimental acceptance. Both fully contained and partially contained events are used.

The histogram in fig. 1, left, shows the distribution of the accepted events as a function of $E_\mu/\cos\theta_\mu$ (energy and zenith of the reconstructed muon) in the absence of oscillations. The points represent the same simulated events, but in an oscillation scenario, i.e. weighting each event with the survival probability $P = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L_\nu/E_\nu)$. The statistics corresponds to three years of data taking and the errors are Gaussian and purely statistical.

To estimate the accuracy with which the mixing parameters can be measured and, conversely, the region of parameter space that can be excluded if no oscillations are found in the data, the following procedure was applied. For different points in the Δm^2, $\sin^2 2\theta$ parameter space, many ANTARES-like experiments were simulated. For each of them, the $E_\mu/\cos\theta_\mu$ distribution was compared to a high statistics simulation without oscillations. The ratio is the neutrino survival probability distribution. An example for the currently most likely values of the mixing parameters is presented in fig. 1, centre.

The survival probability is fitted with a damped oscillation function, $P = 1 - \sin^2 2\theta\,[\,0.5-(0.5-\sin^2 y)exp(-2f^2y^2)\,]$, with $y = (1.27\Delta m^2 L/E)/(1+f^2)$ and y a damping parameter depending on the experimental resolution [4]. Fig. 1, right, shows the region of parameter space where both Δm^2 and $\sin^2 2\theta$ could be measured with an error less than 33% in more than 80% of the simulated experiments.

For the exclusion plot, a χ^2 is calculated for the hypothesis that all the "data" points in the

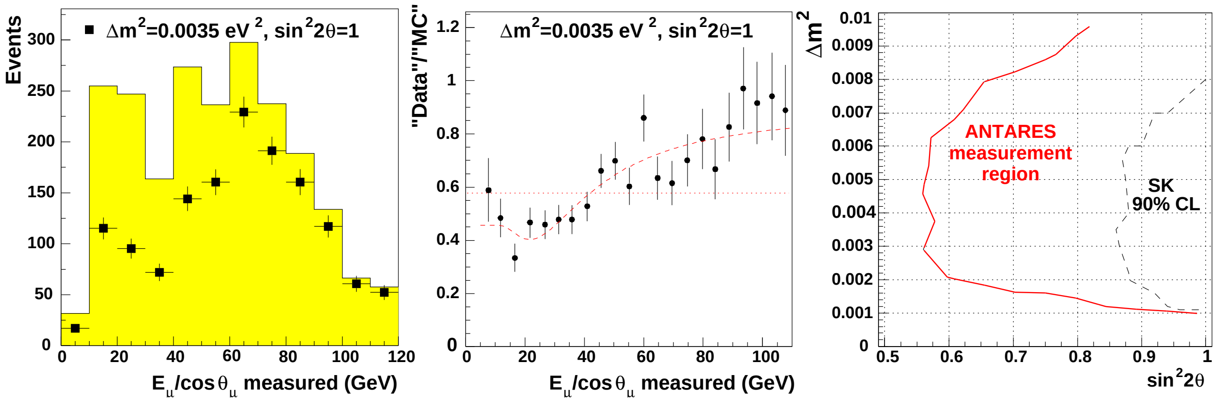

Figure 1. *Left:* expected spectrum of the accepted events in 3 years of data taking in absence of oscillations (solid histogram) and with oscillations supposing $\Delta m^2 = 3.5 \cdot 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta$=1 (squares). The errors are Gaussian and purely statistical. *Centre:* muon neutrinos survival distribution for the same mixing parameters. The damped oscillation fit and the average level are superposed on the data. *Right:* parameter region where ANTARES could measure both Δm^2 and $\sin^2 2\theta$ with an error less than 33%. The dashed line indicates the SuperKamiokande result.

spectrum of fig. 1, left, are compatible with the "no oscillation" distribution. For all the sets of mixing parameters allowed at 90% CL by SuperKamiokande, the probability is less than 10%. Oscillations with those parameters could be therefore excluded at 90% CL if data show no oscillation signal.

The reported analysis assumes that the shape of the neutrino flux is known as a function of energy and angle, but its normalisation is a free parameter. Introducing a 10% systematic uncertainty on the flux shape, the measurement and exclusion regions become smaller, but still cover almost completely the SuperKamiokande allowed region. On the other hand, the non contained muon neutrino events may be used to normalise the contained muon neutrino distribution.

3.1. Conclusions

The ANTARES detector can make useful contributions to the study of the neutrino oscillations: both mixing parameters can be measured with an accuracy better than 33% over a large region of parameter space that covers completely the SuperKamiokande allowed region at 90% CL. The present analysis is preliminary and can be refined in many ways. These first results are encouraging, although further effort is required to understand the systematics.

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