Expected Performance of the ANTARES Experiment

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Abstract

Work is in progress for the development of the software packages that will be used in the ANTARES experiment. Thanks to the good water transparency the estimated angular resolution is a few tenths of a degree allowing a very strong background suppression in the search for point sources. Moreover, new tools are in development to estimate the possibility of performing an analysis on low energy vertical neutrinos. This could allow the study of the energy spectrum between 5-10 GeV and 50 GeV, a region which is particularly sensitive to neutrino oscillations as shown by the recent results of Super-Kamiokande.

1 The ANTARES Project:

The ANTARES project is aimed at the construction of a high energy neutrino detector which will consist of an array of ~ 1000 photo-multiplier tubes arranged in a volume of base area ~ 0.1 km^2 with active height ~ 0.3 km. The site considered for the detector is 20 nautical miles from Toulon (France) in the Mediterranean at a depth of 2400 m. The photo-multiplier tubes are housed in pressure resistant glass spheres. The glass spheres contain the HV power converter to operate the photo-multiplier tube and the electronics circuit (Analogue Ring Sampler) which stores the photo-multiplier tube signals in a buffer, ready for read-out following an event trigger. Three optical modules (OM) are grouped together in a 'story', arranged so the axes of the photo-multiplier tubes point 45° down from the horizontal. At present we plan to use 10-inch Hamamatsu photo-multiplier tubes but developments are underway with other manufacturers for other, possibly larger, tubes. Each story is fixed to a flexible 'string' anchored to the bottom of the sea. In the present design the detector consists of 13 lines, of which 4 contain 41 stories separated vertically by 8 m and 9 contain 21 stories separated vertically by 16 m. In the horizontal plane the lines are arranged in a spiral pattern where the minimum horizontal spacing will be fixed between 60 m and 80 m.

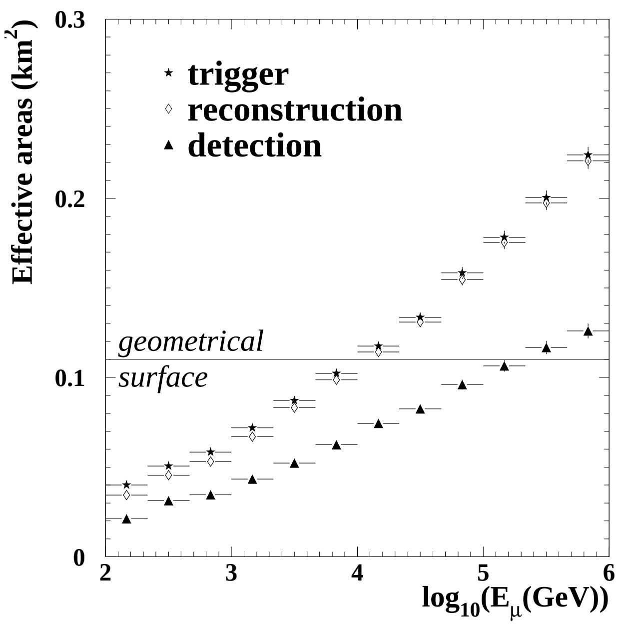

Figure 1: Effective area for triggering, reconstructed and selected events. The areas are averaged for muons coming from the lower hemisphere.

A software package has been developed to simulate neutrino interactions in the medium surrounding the detector, particle tracking and Cherenkov light emission. The response of the detector to the various types of physics events has been studied mainly using a version of the DADA program (Wiebusch, 1995) which originates in the Baïkal collaboration. We have modified this programme for the ANTARES detector and have also made modifications to improve the performance at high energies.

All simulated events include random hits from ^{40}K in the sea water. The string deformation due to the currents has also been simulated. The event reconstruction is made by using the position and the recorded

Model	$\mathbf{E}_\mu^{\rm rec} \geq$ 10 TeV	$\mathbf{E}_\mu^{\rm rec} \geq$ 100 TeV
Atmospheric		
ATM (Volkova, 1980)	68±13	0.8±0.1
Generic AGN models		
SDSS (Stecker, 1991)	251±12	134±10
NMB (Nellen, Mannheim, & Biermann, 1993)	217±9	64±4
Blazars		
PRO (Protheroe, 1996)	34±2	21±2
MRLB (Mannheim, 1995)	7.8±0.4	2.6±0.3

Table 1: Number of accepted muons reconstructed as upward-going above the estimated energy $E_\mu^{\rm rec}$ per year. The errors are statistical.

time for each hit OM. A filter has been developed to remove hits due to ^{40}K. The angular resolution depends on the timing accuracy. The overall timing accuracy is a quadratic sum of the PMT timing error, the error of the OM position (typically 10 cm) and the error in the clock synchronization (expected to be better than 1 ns). The angular resolution for neutrinos with a $1/E_\nu^2$ spectrum is estimated to be 0.2 degrees.

Above 1 TeV the muon energy can be estimated by an algorithm which combines the reconstructed trajectory and the sum of the recorded pulse heights. The error on the energy is a factor of 3 for energies below 10 TeV and a factor of 2 for energies above 10 TeV. Below 100 GeV the muon energy is estimated by measuring its range.

2 Astrophysics:

Figure 1 shows the effective detector area as a function of the true energy for muons induced by high energy neutrinos which trigger the detector, for those which are reconstructed and for those which satisfy our selection criteria. Different models predict diffuse neutrino fluxes from active galactic nuclei (AGN) which could dominate the atmospheric neutrino flux at energies above 10-100 TeV. The event rates expected for these neutrino fluxes and for atmospheric neutrinos have been estimated for events which satisfy our selection criteria and are given in table 1 for 10 TeV and 100 TeV thresholds on the reconstructed energy.

Moreover, due to the extremely low angle between the muon and the parent neutrino and to the good quality of the muon direction measurement, the atmospheric neutrino background contaminating each source can be reduced to a very low level by selecting very small angular regions of the sky. In that way, a signal of only a few events could be significant. The sensitivity of the detector to muon neutrinos can be estimated from measured low-energy gamma-ray fluxes by assuming that *i)* the low energy gamma-rays are of hadronic origin and *ii)* the emitted gamma-rays have a differential energy spectrum E^{-2}.

Using the 2nd EGRET catalog for sources measured during the P12 period, the derived neutrino flux has been extrapolated to the energies where the ANTARES neutrino detector is sensitive.

The detection of the most luminous individual sources could require more than one year of data acquisition. Nevertheless, a statistically significant effect could be detected in one year by adding the contributions of all the extra-galactic sources. The expected number of events is between ten and about one hundred (depending on the value of the differential spectral index used: 2 or 2.2) to be compared to a total background of about 3 events.

The search for neutrinos from gamma ray bursts users the narrow space and time window from the gamma ray information. Here, there is negligible background. With the flux given in (Waxman & Bahcall, 1999) and the effective detector area shown in figure 1, the rate expected is $\simeq 10$ signal events per year with a background rate of less than 0.001 event per year.

3 Neutrino oscillations:

The observation of atmospheric neutrinos for energies below 100 GeV will allow us to study neutrino oscillations for values of the neutrino mass difference Δm^2 between 10^{-3} and 10^{-2} eV^2. An analysis has been carried out using simulated interactions to explore the sensitivity of the proposed experiment to the neutrino oscillation parameters Δm^2 and sin$^2 2\theta$. The simulation used the expected experimental acceptance and the known flux of atmospheric neutrinos. The analysis is based on semicontained events, using for the muon energy the energy visible in the detector. The neutrino flight distance L is related to the zenith angle of the track, θ_z, by $L \sim L_0 \cos\theta_z$, where L_0 is the diameter of the earth, 12740 km.

The histogram in figure 2 shows the distribution of accepted events as a function of $E_\mu/(L_\mu/L_0)$, where E_μ is the muon energy and L_μ is the distance corresponding to the reconstructed muon tracks. This histogram represents a simulation of three years of operation, without neutrino oscillations. The "data" points in figure 2 represent the same simulated events, but with each event weighted with the probability

$$P = 1 - \sin^2 2\theta \sin^2 (1.27\Delta \mathrm{m}^2 \mathrm{L}_\nu/\mathrm{E}_\nu),$$

using the true neutrino values of E_ν and L_ν.

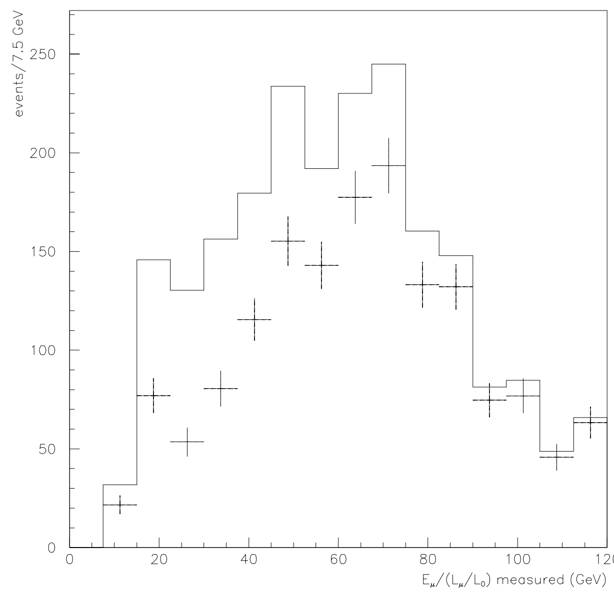

Figure 2: Simulated number of events in 3 years with no oscillations (histogram) and with oscillations for $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 0.0035$ eV^2 (points).

To explore the Δm^2 and sin$^2 2\theta$ parameter space, a series of three-year simulations was carried out as just described, each one producing a distribution like the points shown as crosses in figure 2. Each of these distributions was compared with a high-statistics simulation without oscillations. To remove the effect of absolute normalization, the no-oscillations distribution was multiplied by a factor which was varied as a free parameter. For each point in parameter space a large number of such simulations was carried out. Figure 3 shows the resulting region of parameter space where neutrino oscillations were excluded at the 90% confidence level (CL) in 80% of simulated experiments.

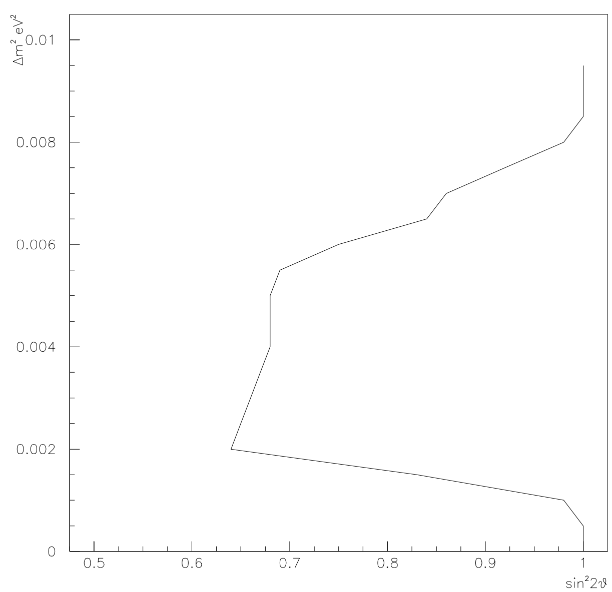

Figure 3: For three years of data taking, the region where neutrino oscillations could be excluded at 90% of CL in 80% of simulated experiments.

It is important to note that the present analysis is exploratory and can be refined in many ways. The ν_μ quasi-elastic events (estimated to about 15% of the charged current ν_μ events) were not included in these simulations. These low energy events have a better correlation between the produced muon and the parent neutrino energy than the deep-inelastic events used here. Inclusion of these events will improve the experimental sensitivity to low Δm^2. On the other hand, the sensitivity will suffer in the real experiment due to systematics resulting from variations in the detector acceptance and assumptions about the neutrino flux and its energy and angular dependence and about backgrounds.

The backgrounds have so far not been taken into account in the analysis. However, making a known background subtraction with the magnitude of backgrounds presently estimated would have little impact on the results. The backgrounds from ν_e and from non-contained ν_μ are related to the atmospheric flux and are well simulated, so a background subtraction can be made. The present simulations indicate the backgrounds from muons originating in the atmosphere are small. These simulations must be refined by including light diffusion in the water, and extended to higher statistics. The detector will have a significant acceptance for events above the horizontal, and these events can be used to control the muon background simulations for events below the horizontal.

References

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