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The ANTARES deep-sea neutrino telescope—Status and first results

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Summary. — The ANTARES neutrino telescope has been accomplished in May 2008. Located at a depth between 2100 and 2500 m in the Mediterranean Sea, 40 km off the Provencal coast, it comprises a large three-dimensional array of 885 Optical Modules deployed on 12 vertical lines. The telescope is aimed to observe high energy cosmic neutrinos through the detection of the Cherenkov light produced by up-going induced muons. The status of the experiment is briefly reviewed, and first results of atmospheric muons and neutrinos analysis will be discussed.

PACS 95.55.Vj – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS 96.50.Vg – Energetic particles.
PACS 29.40.Ka – Cherenkov detectors.

1. – Introduction

The study of cosmic rays is one of the most important topics of astrophysics today. It represents an important step toward the understanding of the Universe. Several gamma-ray sources have been detected in the last few years, however their detection cannot give, up to now, a complete understanding of gamma-ray production mechanisms. If they are produced by hadronics mechanisms, and thus if nuclei are accelerated, then a high energy neutrino counterpart should be observed. Contrary to cosmic rays which are sensitive to magnetic fields, and to photons which are easily absorbed, neutrinos can escape from compact objects, and travel over very large distances without being deflected by magnetic fields, or absorbed by interstellar clouds. Nevertheless, because of the weak interaction between neutrino and matter, very large detectors are needed, and are often installed in hostile environments, where the construction represents a challenge.

ANTARES is a neutrino deep-sea telescope, completed in May 2008, and designed for the detection of high energy neutrinos emitted by Galactic (supernova remnants, micro-quasars, ...) and extragalactic (active galactic nuclei, gamma ray bursters, pulsars, ...) sources. It is also aimed to search for neutrinos induced by dark matter annihilation within massive bodies. Moreover the large area of the detector offers the possibility for

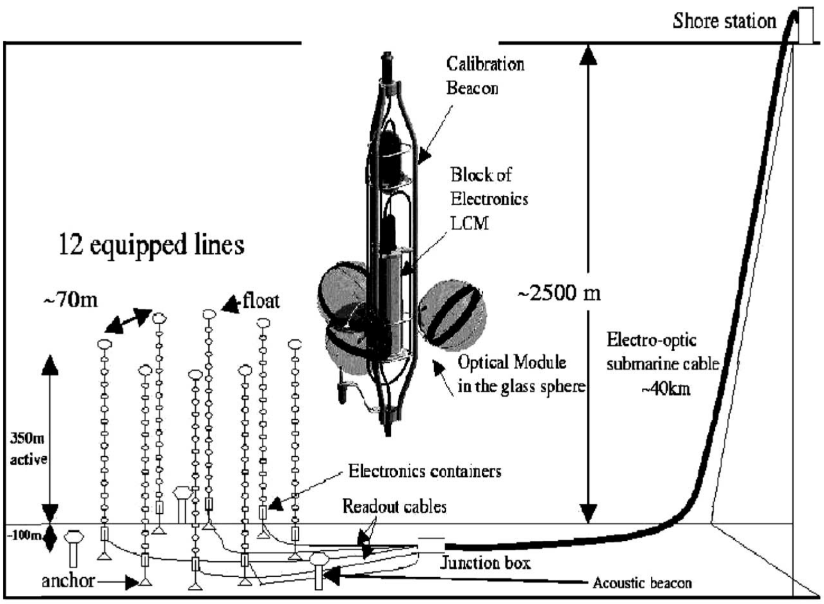

Fig. 1. – Schematic description of the ANTARES detector and of a typical storey containing a LED beacon.

the search for exotic particles such as magnetic monopoles, or nuclearites. ANTARES is the largest neutrino telescope operating in the northern hemisphere, and, by its location, contains the Galactic Centre in its field of view. It provides also a unique platform for multidisplinary sciences as oceanography, sea biology, seismology, or environment monitoring.

2. – The ANTARES detector

The ANTARES neutrino telescope is located at 2475 m depth in the Mediterranean Sea, offshore from Toulon (France) covering an area of about 0.1 km^2 [1]. The detector is composed by 12 flexible lines of 450 m length, which are fixed on the sea bed thanks to an anchor, and are kept taut by a buoy (see fig. 1). They are connected to a junction box which is relied to the shore station with an electro-optical cable of about 40 km. Every line comprises 25 storeys separated by 14.5 m, whose each contains 3 optical modules. Parallel to an optical module, two Analog Ring Samplers [2] are used to digitize signals with amplitude higher than 0.3 photoelectrons. In addition to photodetectors, some storeys contain devices for *in situ* calibrations such as LED Beacons [3], and for acoustic positioning with hydrophones.

The strategy of the ANTARES data acquisition is based on the "all-data-to-shore" concept [2]. This implementation leads to the transmission of all raw data above a given threshold to shore, where different triggers are applied for storage.

3. – Status of the detector and *in situ* calibration

The ANTARES observatory was built gradually until May 2008, giving rise to various detector layouts used for physics analysis: the first two lines were installed, and connected in 2006, then 3 additional lines were plugged at the beginning of 2007, and in December 2007 the detector reached a 10-line configuration. Finally, ANTARES was completed in May 2008, with its final 12-line configuration.

The telescope has an angular resolution of about 0.2^o for high energy neutrinos ($> 10\,\text{TeV}$), it is determined by the intrinsic detector resolution, *i.e.* the timing resolution and accuracy of the location of the optical modules. The time calibration is performed for each line in dark room before their deployment, and is then done regularly *in situ* after the immersion. The relative time calibration relies on several independent systems [4]. The master clock system, by sending redundant signals to each storey, gives the time signal propagation through cables to the shore station. Then to obtain times offsets between optical modules, which depend on the front-ends electronics and on the time propagation inside phototubes, LED optical beacons have been installed every 5 storeys on each line. The flashing light emitted by LED beacons allows to compute time differences between signals received by pairs of optical modules in order to extract their time offsets. Moreover, optical beacons provide the possibility to study optical properties of the sea water, as the light absorption length.

Potassium-40 is a radioactive isotope naturally present in the sea water. Its β-decay gives rise to Cherenkov light produced by electrons, producing a detectable signal in ANTARES. This light is then employed to perform crosscheck of time calibration, by studying coincidences between optical modules of a same storey, and to monitor the evolution of the optical module gains, which are tuned if a significant drift is noticed.

Finally, thanks to these two time calibration methods, a *rms* of $0.6\,\text{ns}$ on the timing precision is reached, in good agreement with the precision of the ANTARES design goal.

4. – Atmospheric muons

Important backgrounds come from biological activities of micro and macro organisms, called bioluminescence, from the dark noise of photomultipliers, and from the ^{40}K decay. The bioluminescence and the dark noise produce irregular hits in the detector, and can be easily removed by searching for correlated hits, corresponding to the crossing of a muon. The light coming from the ^{40}K decay can only illuminate optical modules of a same storey, and are not selected in the reconstruction algorithm when local coincidences between neighbouring floors are chosen.

However, the most of the background is the one produced by atmospheric downgoing muon events. They are produced by high energy cosmic rays interacting with atomic nuclei of the upper atmosphere, with the production of kaons and pions, which decay into muons. At the ANTARES depth, the muon flux exceeds by several orders of magnitudes the atmospheric neutrino-induced muon flux, but can be extracted by regarding only upgoing reconstructed events. Despite they are an important background for neutrino detection, atmospheric muons can be used to verify the detector response. Moreover a deficit of muons in the moon direction will give some important information about the pointing accuracy of the detector.

A first study, recently published in [5], is based on the observation of coincidence signals in adjacent storeys of the detector, yielding to a low energy threshold of $4\,\text{GeV}$, in

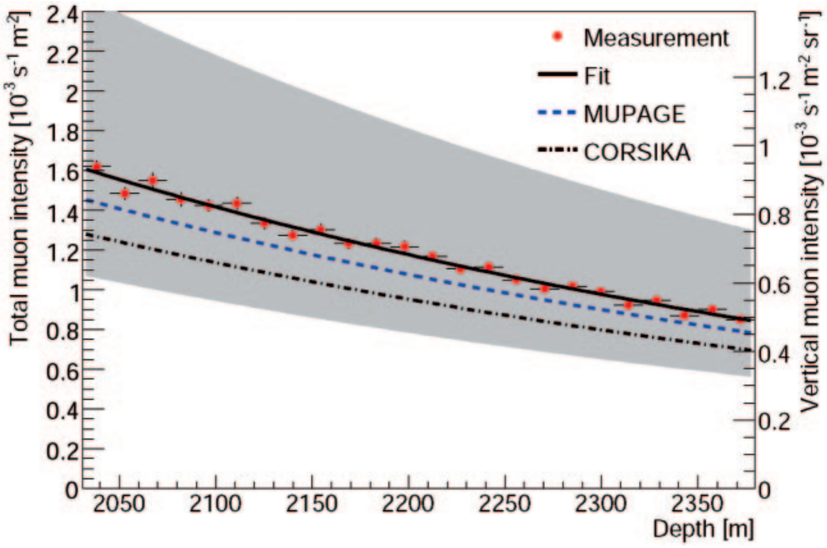

Fig. 2. – (Colour on-line) Depth dependence of the total atmospheric muon flux as measured from coincidence signals on adjacent floors (red points). The measured flux dependence is compared to results from Monte Carlo simulations performed with CORSIKA [7] (dash-dotted black line), using the NSU model [8], and MUPAGE [6] (dashed blue line). The grey band shows the normalisation uncertainty of data.

order to measure the attenuation length of the muon flux. Figure 2 shows the coincidence rates measured in different storeys as a function of depth for atmospheric downgoing muons. The measured depth dependence of the rates can be very well fitted with the expected exponential fall-off of the muon intensity, and is compatible with Monte Carlo simulations performed with MUPAGE [6], and CORSIKA [7] with the NSU model of the primary cosmic ray spectrum [8]. The results are also consistent with previous analysis performed using a full track reconstruction and by converting the reconstructed zenith angle into an equivalent slant depth through the sea water [9].

5. – ANTARES first neutrino events

The online reconstruction method isolates in real time upward going neutrino-induced muon candidates by applying a simple cut on the track fit quality. For 2007 and 2008 (~ 341 days of effective livetime), about 750 upgoing muons have been reconstructed in ANTARES. These events, reconstructed on at least two strings, are shown fig. 3 as a function of their elevation. From atmospheric neutrino simulations, based on the Bartol flux [10], and downgoing atmospheric muons simulations, which uses Corsika [8] with the NSU primary composition [8], one obtains very good agreements with the reconstructed data, with an expected contamination of the neutrino sample less than 4% from mis-reconstructed atmospheric muons. The agreement with Monte Carlo expectations gives the confidence in the simulation of the detector and of the event reconstruction for downgoing reconstructed muons, confirming a correct understanding of the detector. For the systematic errors the optical modules properties, and the uncertainties in the sea water description are considered. They are larger for downgoing events because of the optical modules orientations (45° downward looking).

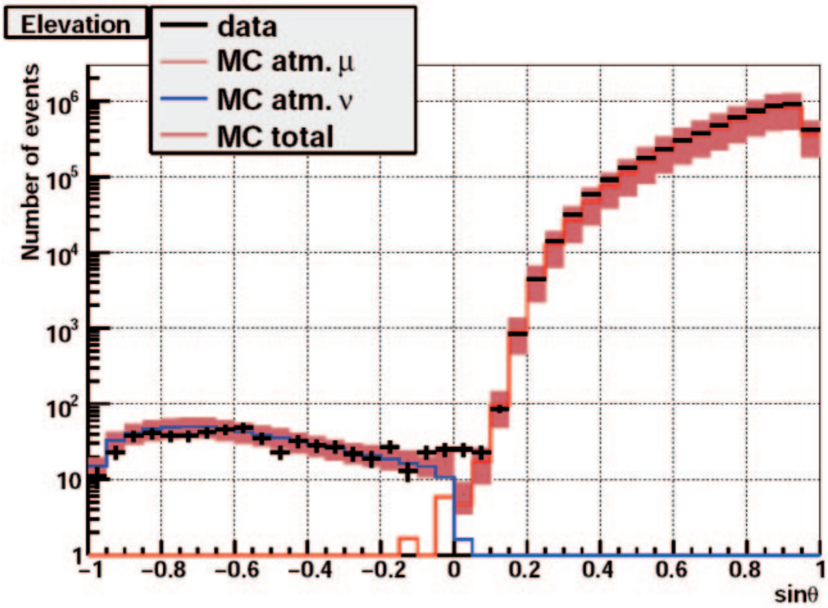

Fig. 3. – (Colour on-line) Elevation of reconstructed data (black crosses) from 2007 and 2008 on at least two strings. The distribution is compared to muon (red line) and neutrino (blue line) simulations, respectively performed according to the NSU primary composition [8], and the Bartol flux model [10].

The 750 upgoing reconstructed events are then selected, and are presently used for the search of cosmic point-like sources. A scrambled sky map of these events is shown in fig. 4 in Galactic coordinates. The grey scale represents the exposure time of ANTARES, which can see the interesting center of the Galaxy. The scrambling, consisting in changing randomly the time of the events, has been employed to avoid any human bias in the analysis.

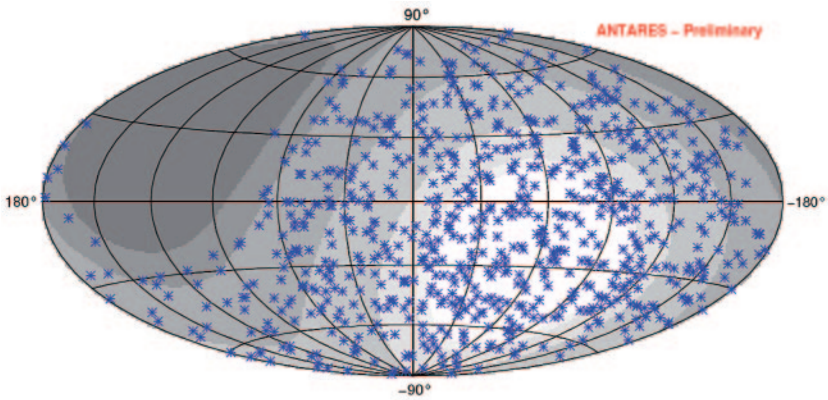

Fig. 4. – (Colour on-line) Scrambled sky map of 750 neutrino candidates (blue crosses) taken from 2007 and 2008 data (∼ 341 days of effective livetime). The grey scale represents the exposure time of ANTARES, from permanent (in white) to null exposure (in dark grey).

6. – Conclusion

ANTARES has been completed in May 2008. It is the largest operational neutrino telescope of the northern hemisphere, taking data with a high duty cycle. The flux of atmospheric muons has been measured and is found to be in agreement with Monte Carlo expectations. The detector is now well understood, and very good agreements are obtained with Monte Carlo simulations, performed for atmospheric muons and neutrinos. The first physics analysis for the 2007 and 2008 data are in their finalisation steps, and will be presented in the next few months.

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