Neutrino astrophysics with the ANTARES Cherenkov Detector

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Abstract. The ANTARES neutrino telescope is currently the largest water Cherenkov detector in operation in the Northern Hemisphere. The detector is a lattice of 885 Optical Modules distributed over 12 lines, located 40 km off the Southern French coast at a depth of about 2500 m. Its main scientific goal is the detection of high energy cosmic neutrinos from galactic and extra galactic sources using the Cherenkov photons emitted along the pattern of neutrino-induced charged leptons. The detector has been taking data regularly since 2006 in a partial configuration and has been completed in Spring 2008. The status of the experiment is reported and a selection of the latest results is discussed. In particular, this paper presents the up to date upper limits for diffuse high-energy cosmic neutrino flux, the searches for point sources, the multi-messenger analyses and the measurement of the neutrino oscillations.

1. Introduction

It is difficult to determine the role of the hadronic and leptonic interactions in the most violent phenomena in the Universe using solely the photon observations. Measurement of ultra-high energy neutrinos would enhance our understanding of the accelerating regions of both galactic and extra galactic objects. Pion production after hadronic interaction could generate a significant flux of neutrinos from point-like sources as well as a diffuse neutrino background. Due to the small neutrino cross-section, the volume of the detector must be large. This can be achieved using naturally abundant material like water or ice, in which detection of the charged lepton counterpart of the neutrinos is possible [1]. The ANTARES detector is located 2500 m deep in the Mediterranean Sea, at about 40 km off the French coast and is optimized to measure muons in the 100 GeV-100 TeV range.

2. The ANTARES detector and submarine infrastructure

The ANTARES detector [2] consists of 885 Optical Modules (OM), each one housing a 10″ PMT. The OM are mounted in groups of three along 12 detection lines distributed in a volume of 0.05 km³. The lines are anchored to the sea floor and held upright by buoys. Each OM triad is a node of a submarine network which is connected to the computing farm on shore by a 50 km electro-optical cable (EOC). The acoustic positioning system grants a spatial resolution better than 20 cm, while a system of optical beacons allows a time resolution of about 2 ns.

In the fall of 2010, a secondary submarine infrastructure was placed and connected to the main EOC to support a network of four seismic stations in the framework of the DeepSeaNeT project [3].
3. Astrophysics research

The OMs of the ANTARES detector are looking downwards to have maximum efficiency for events induced by neutrinos after traversing the Earth. Thus the background of muons from atmospheric showers can be suppressed by about $1 : 10^6$ after applying quality cuts on the muon candidates. An irreducible background of neutrinos produced in atmospheric showers in the field of view has to be considered in all searches for cosmic neutrinos.

3.1. Diffuse fluxes

Using data from 334 days of equivalent live time an upper limit for the diffuse cosmic $\nu_\mu + \bar{\nu}_\mu$ flux could be determined [4], assuming the Waxmann-Bahcall upper bound [5] as the reference flux. A very strict event selection was required to eliminate the background from misreconstructed atmospheric muons. The original energy estimator $R$ was introduced in [4], which relies on the rising energy loss of muons through radiative processes with increasing energy. As atmospheric neutrinos are expected at a generally lower energy than their cosmic counterparts, event selection based on $R$ further increases the sensitivity of the measurement. The 90% C.L. upper limit of $E^2 \Phi_{90\%} = 5.3 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at 90% confidence level was set in the energy range: $20 \times 10^3$ GeV $\leq E_\nu \leq 2.5 \times 10^6$ GeV.

3.2. Point sources

Using 4 years of data (2007-2011), two different approaches were adopted for the search of point sources. In the first approach, a time-integrated full-sky search was performed, whereas the second search focused on 51 neutrino source candidates of various types. Pseudo-experiments are used to estimate the sensitivity of the analysis, which is carried out optimizing the discovery potential for the given flux and sources. In the full-sky search, the most significant cluster was found at R.A. = -46.5$^\circ$ and $\delta$ = -65.0$^\circ$ at the level of significance of 2.2$\sigma$. Within the candidate search, the most signal-like source was HESS J1023-575 with a post-trial p-value of 41%. The obtained upper limits on the flux of neutrinos from the candidate sources are shown in figure 1 together with the expected 90% C.L. sensitivity level for ANTARES. More details are given in [6] and updates in [7] in these proceedings.

![Figure 1. Limits set on the $E^2$ flux for the 51 sources in the candidate list. The ANTARES sensitivity of this analysis is shown as a solid line and the IceCube 40 sensitivity as a dashed line. The references for the shown measurements can be found in [7].](image1)

![Figure 2. Preliminary 90% C.L. flux upper limits (colored lines) compared to the theoretical flux without cutoff (black line) expected from the Fermi Bubbles.](image2)
3.3. Neutrinos from Fermi Bubbles
The so-called Fermi Bubbles [8] could represent a possible source of galactic high energy neutrinos. A recent analysis of 2007-2010 data, for a total livetime of 588 days, followed the off-zones approach [9]. Assumed as a reference for the measured background, the off-zones are portions of the sky where no signal is expected. Three off-zones, with the same shape and visibility of the one built around the Fermi Bubbles (called on-zone), limit the systematic differences for the expected background within less than 3%. Quality cuts are set by using the Model Rejection Factor [10] approach and assuming a signal flux with a 100 TeV cutoff. The preliminary result of the selected events from the off-zones (combined) \(N_{\text{bkg}} = 90 \pm 5 \text{ (stat)} \pm 3 \text{ (sys)}\) and from the on-zone \(N_{\text{sig}} = 75\) is conformal with the assumption of background. Figure 2 shows the 90% C.L. upper limits computed according to [11] for fluxes with no cutoff and 50, 100, 500 TeV cutoff, in the energy range \(10^2-10^6 \text{ GeV}\).

3.4. Multimessenger searches - 1. Optical Follow-up
Astrophysical transient sources such as \(\gamma\)-ray bursts (GRB), core collapse supernovae and flaring active galactic nuclei are supposed to produce high energy neutrinos. To enhance the sensitivity of ANTARES to such sources, a new detection method based on coincident observations of neutrinos and optical signals from the TAROT/ROTSE, ZADKO/SkyMapper and SWIFT observatories has been developed [12]. A fast online muon track reconstruction is used to trigger a network of small automatic optical telescopes with a latency less than 10 s. Such alerts are generated for special events, e.g. two or more neutrinos, coincident in time and direction, or single neutrinos of very high energy. Since mid 2009, more than 50 neutrino alerts triggered the follow-up. No optical counterparts brighter than 16.2 were found, limiting the magnitude associated to a high energy neutrino within 75 s from the neutrino alert.

3.5. Multimessenger searches - 2. Gravitational Waves
The association of high energy neutrino candidates with possible gravitational wave bursts could reveal new, hidden sources that are not observed by conventional photon astronomy, such as the failed GRBs, as well already observed microquasars and soft \(\gamma\)-ray repetitors (SRG). A preliminary search uses neutrinos detected by ANTARES in its 5 lines configuration from January to September 2007 [13]. Such a time interval coincided with the fifth and first science runs of LIGO and Virgo, respectively. The LIGO-Virgo data were analysed for candidate gravitational-wave signals coincident in time and direction with the neutrino events. No significant coincident events were observed. By assuming a gravitational-wave energy of \(E_{\text{GW}} \sim 10^{-2} M_\odot^2\) \((M_\odot\) is the Solar mass), exclusion distances larger than 1-10 Mpc are set for core-collapsing objects, such as coalescent systems made by a neutron star and a black hole or two neutron stars (see figure 3).

4. Beyond Astrophysics
The scope of the ANTARES detector is suitable for a diverse field of physics and a large number of analyses is currently ongoing e.g. searching dark matter [14], magnetic monopoles and nucleartes [15], available in these proceedings .

A successful test of the physics capabilities of ANTARES has been conducted in a measurement of the atmospheric neutrino two-flavour oscillation parameter \(\Delta m^2_{32}\). The data taken refer to the period 2007 -2010, for a total live time of 863 days. Muon tracks are reconstructed with energies as low as 20 GeV. Neutrino oscillations cause a suppression of vertical upgoing muon neutrinos of such energies crossing the Earth. The parameters determining the oscillation of atmospheric neutrinos are extracted by fitting the event rate as a function of the ratio of the estimated neutrino energy \(E_R\) and reconstructed flight path (which is proportional to the cosine of the zenith angle \(\Theta_R\)) through the Earth (see figure 4). Assuming maximal
mixing, a mass difference of $\Delta m^2 = (3.1 \pm 0.9) \times 10^{-3}\text{eV}^2$ is obtained, in good agreement with the world average value. A more detailed discussion is presented in [16].

References

[1] Chiarusi T and Spurio M 2010 *Eur. Phys. J.* C **65** 649
[2] Aguilar J et al 2011 *Nucl. Instrum. Methods* A **656** 11–38
[3] Valdy P 2011 *Global Change: Mankind-Marine Environment Interactions* ed Ceccaldi H J, Dekeyser I, Girault M and Stora G (Springer Netherlands) pp 299–305
[4] Aguilar J et al 2011 *Physics Letters* B **696** 16–22
[5] Bahcall J and Waxman E 2001 *Phys. Rev. D* **64** 023002
[6] Adrian-Martinez et al 2011 *Astrophys. J. Lett.* **743** L14
[7] Gomez-Gonzalez J P 2012 *Proc 23rd ECRS (Moscow)* Submitted to *J. Phys.: Conf. Series* (MN 392)
[8] Meng S, Slatyer T R and Finkbeiner D P 2010 *Astrophys. J.* **724** 1044
[9] Kulikovskiy V 2012 *Nucl. Phys. B - Proc. Suppl.* in press
[10] Hill G C and Rawlins K 2003 *Astropart. Phys.* **19** 393–402
[11] Rolke W A, Lopez A M and Conrad J 2005 *Nucl. Instrum. and Meth.* A **551** 493 – 503
[12] Ageron M et al 2012 *Astropart. Phys.* **35** 530
[13] Adrian-Martinez S et al 2012 Preprint arXiv:1205.3018v2 [astro-ph.HE]
[14] Lambard G and Gomez Gonzalez J P 2012 *Proc 23rd ECRS (Moscow)* Submitted to *J. Phys.: Conf. Series* (MN 436)
[15] Pavalas G 2012 *Proc 23rd ECRS (Moscow)* Submitted to *J. Phys.: Conf. Series* (MN 543)
[16] Adrian-Martinez S et al 2012 *Phys. Lett.* B **714** 224–230