First results from the ANTARES neutrino telescope

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The ANTARES detector is the most sensitive neutrino telescope observing the southern sky and the world’s first particle detector operating in the deep sea. It is installed in the Mediterranean Sea at a depth of 2475 m. As an example of early results, the determination of the atmospheric muon flux is discussed and a good agreement with previous measurements is found. Furthermore, the results of a search for high-energy events in excess of the atmospheric neutrino flux are reported and significant limits are set on the diffuse cosmic neutrino flux in the multi-TeV to PeV energy range. Using data from more than 800 days of effective data taking, partly during the construction phase, a first analysis searching for point-like excesses in the neutrino sky distribution has been performed. The resulting sensitivity of ANTARES is reported and compared to measurements of other detectors. A method employed for a first search for neutrinos from Fermi-detected gamma-ray flaring blazars in the last 4 months of 2008 is described and the results are reported. No significant neutrino signal in excess of that expected from atmospheric background has been found.

1. INTRODUCTION

The goal of high-energy neutrino astronomy is to provide a new view of the Universe by detecting the messengers emitted from its most violent regions. The emission of high-energy neutrinos necessarily implies the presence of highly relativistic baryons at the acceleration sites and consequently provides incontrovertible evidence for the acceleration of charged cosmic rays. The observable neutrino flux is expected to be generated mainly through charged pion production in collisions of high-energy protons from the cosmic ray accelerators with the ambient gas or with radiation fields [1]. These neutrinos will point back to even very distant sources, as they are neither absorbed nor deflected, a property that makes these particles unique astronomical messengers [2]. High-energy neutrinos can be of galactic and extragalactic origin. Supernova remnants and micro-quasars are examples for candidate sites in our Galaxy, while gamma-ray bursts and active galactic nuclei represent promising potential extragalactic sources [3]. Due to the extremely low cross section of neutrino interactions, neutrino detectors need to instrument very large volumes and should be built in a low background environment. The current neutrino telescopes exploit the idea, proposed by Markov [4], of instrumenting a large volume of water or ice, in order to detect the charged leptons (in particular muons) emerging from charged-current neutrino-nucleon interactions. For a list of recent reviews see [5].

2. THE ANTARES DETECTOR

The ANTARES detector [6] (see Fig. 1 for a schematic view) is located at a depth of 2475 m in the Mediterranean Sea (42° 48’ N, 6° 10’ E), 42 km from the French city of Toulon. It is equipped with 885 optical sensors arranged on 12 flexible lines. Each line comprises up to 25 detection storeys, each equipped with three downward-looking 10-inch photomultipliers (PMTs), oriented at 45° relative to the vertical. Each PMT is installed in an Optical Module (OM) that consists of a 17-inch glass sphere in which the optical connection between the PMT and the glass is assured by an optical gel. Each line is roughly 450 m long and is held tight by a buoy at its top. The spacing between storeys is 14.5 m. The distance between adjacent lines is of the order of 60 – 70 m. ANTARES contains in addition a line (IL07) with oceanographic sensors dedicated to the measurement of environmental parameters. ANTARES therefore represents an important multidisciplinary deep-sea research infrastructure delivering unique data to marine biologists and oceanographers. The construction of the ANTARES detector took place in several sea campaigns starting in the year 2006 and has been completed in May 2008 with the deployment and connection of the last 2 lines. Due to this long construction phase and the modularity of the detector, the commissioning phase comprised several detector configurations with different numbers of active lines. The neutrino detection relies on the emission of Cherenkov photons by high-energy muons originating from charged-current neutrino-nucleon interactions in or around the instrumented volume. From the PMT positions and the relative arrival times of the Cherenkov photons at the PMTs, and making use of the characteristic emission angle of Cherenkov radiation, the trajectory of the muon can be reconstructed. The direction of incident neutrinos can be inferred with an energy dependent precision that is expected to be better than 0.3 degrees for $E_\nu > 10$ TeV. As the detector lines move with the deep-sea current, the position of the OMs need to be monitored to ensure this excellent angular resolution. The position of the OMs is determined every 2 minutes by means of an acoustic triangulation system, while the orientation of each storey is measured with a compass and a tiltmeter. The timing calibration [7], which is also crucial for the angular resolution and very stable in time, is monitored regularly in-situ with dedicated pulsed
light sources distributed along the lines.

3. ATMOSPHERIC MUON FLUX

The main goal of a neutrino telescope is to detect high-energy neutrinos from extraterrestrial sources. However, the signal observed by ANTARES is dominated by muons that are generated in cosmic ray interactions in the atmosphere above the detector and which have sufficient energy to reach the detector at its average installation depth of 2200 m below sea surface. The muon flux measured at the ANTARES site is an important test beam to study detector systematics and to validate the reconstruction algorithms employed. Two different studies of the depth-intensity relation for muons have been carried out. In the first, the attenuation of the muon flux as a function of depth is observed as a reduction in the rate of photon coincidences between adjacent storeys along the detection lines [8]. This method has the advantage that it does not rely on any track reconstruction method and therefore allows for testing directly the response of the detector. The second method is based on a standard tracking algorithm that allows for reconstructing the (average) zenith angle of the incident muon (bundle) which is then used to compute the track length from the sea surface to the detector. This track length is usually called “equivalent slant depth”. Taking into account the known angular distribution of the incident muons, a depth-intensity relation can be extracted [9]. The results are in good agreement with previous measurements as can be seen from Fig. 2. The rather large error band is mainly due to the systematic uncertainty on the determination of the absorption length of light in water and of the angular acceptance of the OMs at large angles, which becomes important for muons traversing the detector from above due to the downward-pointing setup of the OMs.

4. SEARCH FOR A DIFFUSE NEUTRINO FLUX

The prediction of a neutrino flux from extraterrestrial sources is a direct consequence of the observation of high-energy particle and gamma radiation impinging on the Earth’s atmosphere [10]. While both elec-
Figure 2: Vertical flux of atmospheric muons as a function of the equivalent slant depth (taken from [9]), measured with 5 lines of the ANTARES detector during the construction phase in 2007.

Electrons and charged hadrons can be present at cosmic acceleration sites, only in the case of hadron acceleration will the energy escaping from the source be distributed between the cosmic ray component, gamma rays and neutrinos. A spatially unresolved, hence diffuse, flux of such high-energy neutrinos resulting from different cosmic sources has been predicted by various authors. There are two relevant upper bound estimates: Waxman and Bahcall (W&B) [11, 12] use as a constraint the cosmic ray flux measurements at energies $E_{CR} \approx 10^{19}$ eV; Mannheim, Protheroe and Rachen (MPR) [13] consider the diffuse $\gamma$-ray flux in addition. For sources that are assumed to be transparent to neutrinos, the resulting upper limits are shown in Fig. 3. The search method for the diffuse neutrino flux exploits the fact that the atmospheric neutrino flux, which constitutes the main background in this search, has been measured to exhibit a $E^{-3.7}$ dependence at high energies. The predicted diffuse flux of cosmic neutrinos, however, is expected to follow the much harder energy spectrum of its parent hadron distribution, i.e. a spectrum with a spectral index close to -2. This prediction results from the fact that the only known mechanism that can accelerate cosmic ray particles up to the highest observed energies is the so called Fermi acceleration expected to occur in hydrodynamical shock fronts. To separate atmospheric and diffuse cosmic neutrino fluxes, a robust energy estimator for high-energy muon neutrino events has been developed for ANTARES. The algorithm is based on the average number of hit repetitions ($R$) in the OMs due to the different arrival times of so called direct and delayed photons. The number of hit repetitions for a specific OM in a single event is defined as the number of hits measured in a time interval up to 500 ns after and including the first hit that is used for the muon track reconstruction. The estimator $R$ is calculated as the average number of repetitions, dividing the sum of the number of repetitions in the individual OMs by the number of all OMs that contribute at least one hit selected by the track reconstruction algorithm. Direct photons reach an OM without being scattered on their way from their Cherenkov vertex along the muon track, whereas scattered Cherenkov photons or photons induced by electromagnetic showers along the muon track are referred to as delayed with arrival time differences up to hundreds of nanoseconds with respect to direct photons. For high muon energies ($E_{\mu} > 1$ TeV) energy loss contributions due to radiative processes start to dominate and increase linearly with the muon energy, thus leading to additional delayed light in the detector due to electromagnetic showers. This is exploited to select neutrino events and to finally discriminate between atmospheric background and cosmic neutrinos. Using a large set of atmospheric muon and neutrino Monte Carlo events, for which the detector response was fully simulated, the event selection has been optimised before the signal region was uncovered for the data. The atmospheric neutrino background was modelled following the Bartol flux parametrisation [16] with an additional high-energy component induced by the decay of charmed mesons (prompt component) [17]. The signal neutrino flux $\Phi$ was modelled with a $E^{-2}$ spectral shape. The discrimination of signal and background neutrinos is achieved by a single cut on the hit repetition value $R$ of the above defined energy estimator. This cut has been optimised to maximise the detector sensitivity using Monte-Carlo events only. The expected number of remaining atmospheric neutrino events is
Figure 3: The ANTARES upper limit (90% C.L.) for a $E^{-2}$ diffuse high-energy $\nu$ + $\bar{\nu}$ flux (taken from [17]), compared with limits from other experiments and theoretical predictions for transparent sources. The factor 1/2 for the W&B and the MPR model accounts for neutrino oscillations. While the central red line represents the average atmospheric neutrino flux, the grey band denotes the uncertainty due to incident angle and different neutrino production channels [14].

11 ± 2. The systematic uncertainties are dominated by the uncertainty on the atmospheric neutrino flux and the detector acceptance including its dependence on environmental parameters. Data taken during the years 2007 to 2009 with an equivalent live time of 334 days and with several different detector configurations are used for the analysis. After applying the same cut on the data, 9 neutrino candidate events remain, in full agreement with the background assumption. This result translates into an upper limit (90% C.L.) for the diffuse cosmic neutrino flux of $E^{2} \Phi_{90\%} = 5.3 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This limit [17] holds for an assumed $E^{-2}$ signal spectrum and in a neutrino energy range $20$ TeV < $E_{\nu}$ < $2.5$ PeV. Models yielding spectral shapes different from the generic $E^{-2}$ have been tested and some of them could be excluded (cf. [17] and ref. therein) at the 90% confidence level.

5. NEUTRINO POINT SOURCE SEARCH

5.1. Time-integrated search

A search for cosmic sources of muon neutrinos has been carried out using data collected in the years between early 2007 until the end of 2010, corresponding to an integrated live time of 813 days. An earlier version of this analysis using data collected in 295 days can be found in [18]. The muon reconstruction algorithm employed is based on a maximum likelihood fit and yields the track direction, a reconstruction quality parameter based on the reduced log-likelihood of the track fit and an estimate of the angular error. Using a full detector simulation, an average angular resolution of 0.5° ± 0.1°, defined as the median angle between the neutrino and the reconstructed muon direction, has been determined for a $E^{-2}$ neutrino spectrum. Optimising the limit setting and discovery potential at the same time, only upward-going events with a good reconstruction quality and an angular error estimate better than 1° are selected. The resulting event sample consists of 3058 up-going event candidates. MC simulations indicate that 84% of these can be expected to be neutrinos, while 16% are expected to be misreconstructed downward atmospheric muons. As the signature of a point source is a cluster of events at a given celestial position, two different analyses, both using an unbinned maximum likelihood method employing the angular resolution and the declination-dependent rate of background events, are applied to the up-going event sam-
Figure 4: Preliminary flux limit (90% C.L.) vs. source declination for a list of 50 potential neutrino sources in the ANTARES field of view. The sensitivity (blue dashed line) is given as the median of the flux limits for the tested sources.

ple, in order to search for such clusters. In each case, the likelihoods for the assumption that the cluster under inspection is induced by pure background or by an additional source contribution of unknown intensity are computed and their ratio is used to distinguish between signal-like clusters and clusters induced by background fluctuations. In the first analysis the full sky is searched for point sources, while in the second analysis neutrinos are searched for only in the direction of 50 predefined celestial positions, corresponding to well known galactic and extragalactic astrophysical objects that could be powerful cosmic accelerators and potential neutrino sources [19]. These candidate sources were selected according to their observed GeV to TeV gamma-ray fluxes, whereby no temporal coincidence of the gamma-ray emission with the analyzed data was required. Neither search yielded a significant excess of events over the expectation from pure atmospheric neutrino background. The post-trial probability of the most signal-like cluster of events at \((\alpha, \delta) = (-46.5^\circ, -65.0^\circ)\) for the full sky search to be compatible with a fluctuation of the atmospheric neutrino background is 2.5% (p-value) and consequently the hypothesis of a neutrino point source at these coordinates must be rejected as insignificant. The candidate search yields the object HESS J1023-575 as the source associated with the most signal-like cluster. The probability, however, for a background fluctuation resulting in a cluster at least as significant as the observed one, is 41%. Consequently, as no excess neutrino signal has been observed with sufficient significance, upper limits have been set on the flux for each individual source candidate assuming an \(E^{-2}\) spectrum. The individual limits and the ANTARES sensitivity as a function of declination and computed as the median of the limits are reported in Fig. 4. The limit computation is based on a large number of simulated experiments in which systematic uncertainties on the angular resolution and the acceptance are taken into account. The obtained upper limits are more stringent than those from previous experiments in the Northern hemisphere (observing the Southern sky) and competitive with those set by the IceCube observatory [20] for declinations \(\delta \lesssim -30^\circ\). The various experiments are sensitive in different energy ranges, even though they all set limits on \(E^{-2}\) spectra. For such a spectrum, ANTARES detects most events at energies in a broad range around 10 TeV, which is a relevant energy range for several galactic source candidates.

5.2. Search in coincidence with gamma-ray flaring blazars

By design, neutrino telescopes constantly monitor at least one complete hemisphere of the sky and are thus well set to detect neutrinos produced in transient astrophysical sources. The importance of the irreducible neutrino background originating from Earth’s atmosphere can be drastically reduced by selecting
Blazars are particularly interesting as potential neutrino point sources as their enormous energy output in the form of electromagnetic radiation and their relativistic outflow of collimated streams of matter make them good candidate sources of ultra high-energy cosmic rays. As a consequence, neutrinos and gamma-rays may be produced in interactions of accelerated hadrons with intense ambient photon fields or matter. The gamma-ray light curves of blazars measured by the LAT instrument onboard the Fermi satellite reveal important time variability on a timescale of hours up to several weeks, with high-state intensities mostly several times larger than the typical flux of the source in its quiescent state. Assuming a hadronic origin of the observed gamma-rays, it is assumed in the following that the observed time-variable gamma-ray fluxes and the expected associated neutrino fluxes are proportional. Therefore, high states of gamma-ray activity in a source are used to define time windows for the neutrino search from this source. The ANTARES data used in this first coincidence search corresponds to the period from September 6th to December 31st, 2008 and were taken with the complete detector in its 12-line setup. Periods with high bioluminescence-induced optical background have been excluded, which results in an effective live time of 60.8 days. The algorithm for a point source search with time dependence factorizes the probability of a given event to be signal or background into a directional and a time component. The probability density function describing the background contribution is derived from data using the observed declination distribution of the selected neutrino candidate events and the time distribution of all reconstructed muons. The probability density for the signal is described by the telescope's point spread function and by the gamma-ray light curve of the source under inspection. Using a method that maximizes the likelihood ratio of signal and background, the average number of signal events required to achieve a 5\sigma discovery with 50% probability can be computed as a function of the flare duration. For a test flare with a constant flux light curve from a source at a declination of \( \delta = -40^\circ \), it has been shown (cf. \cite{23} for details) that the discovery potential of the telescope improves at least by a factor of 2 for flare durations shorter than a day compared to the standard time integrated point source analysis. This time-dependent analysis has been applied to bright and variable blazars reported in the first year Fermi LAT catalogue \cite{24} and in the LAT Bright AGN sample \cite{25}. Only sources in the field of view of ANTARES were selected whose average high-state photon flux for gamma energies above 300 MeV in bins of one day duration was greater than \( 20 \times 10^{-8} \text{cm}^{-2} \text{s}^{-1} \) and that showed significant time variability in the studied time period. The resulting list includes six Flat Spectrum Radio Quasars and four BL Lacs. The most significant source is the blazar 3C279, which has a pre-trial p-value of 1%. The unbinned method described above finds one high-energy neutrino event located at
0.6° from the source location during a large flare in November 2008. Fig. 5 shows the time distribution of the Fermi gamma-ray light curve of 3C279 and the time of the coincident neutrino event [23]. This event has been reconstructed with 89 hit optical modules distributed over 10 out of 12 detection lines. The error estimate on the reconstructed direction, derived from the maximum-likelihood track fit, is 0.3°. The post-trial probability is computed taking into account the search for ten different objects. The final probability to find a signal at least as significant as the one observed amounts to 10%. Hence, the observed neutrino can be attributed to the atmospheric background. The energy information of the neutrinos has not been used in this analysis up to now.

6. CONCLUSION AND OUTLOOK

The ANTARES neutrino telescope started routine data taking in a configuration with 5 installed lines in 2007. Since May 2008 this first-generation telescope is complete and has in the meanwhile recorded a large neutrino sample of high quality. The feasibility of installation and operation of a particle physics detector in the hostile environment of the deep sea has been demonstrated and first results have been obtained. The search for a cosmic diffuse high-energy neutrino flux and a search for steady point sources both resulted in stringent and competitive upper limits for the flux of cosmic neutrinos. In order to increase the discovery potential, a first step towards multi-messenger searches has been made by using Fermi-LAT gamma-ray flux data to narrow the search time windows for neutrino production. The main assumption made is that the gamma-ray and neutrino fluxes are proportional. One neutrino has been found in coincidence with a gamma-ray flare of a Flat Spectrum Radio Quasar during the last 4 months of the year 2008, but can be explained by the atmospheric background. The successful operation of the ANTARES neutrino telescope is an important step towards KM3NeT [26], a future multi-km³-scale high-energy neutrino observatory and marine science infrastructure proposed for construction in the Mediterranean Sea.

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