Nuclear Instruments and Methods in Physics Research A 692 (2012) 197–200

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Towards acoustic UHE neutrino detection in the Mediterranean sea

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ARTICLE INFO

Available online 6 February 2012

Keywords:
Underwater neutrino telescope
KM3NeT
Calibration
Acoustic positioning system
Acoustic detection

ABSTRACT

Acoustic detection is proposed as a promising detection technique for Extreme High energy neutrinos. This technique is based on the detection of the acoustic signature of neutrino-induced showers in water: a bipolar signal, having a bandwidth of few 10 kHz, with cylindrical wave front. During the last decade, the possibility of access to deep-sea infrastructures developed for Cherenkov telescopes, allowed start-up of intense R&D activities on acoustic detection. In the framework of the activities of ANTARES, NEMO and KM3NeT, several small size experiments were run in order to measure acoustic noise in deep sea and test “neutrino-like” acoustic event detection. These activities have set milestones both for future HE neutrino detectors, for innovative deep-sea technology and for Earth-Sea science. A review on acoustic neutrino detection and projects running in the Mediterranean Sea is presented.

1. The physics case

In the last decade, the field of astro-particle physics entered in a flourishing period thanks to the operation of several experiments that lead to discovery and identification of about a hundred cosmic gamma-ray sources emitting $>$TeV (10^{12} eV) photons ([1]), and to the measurement of the Ultra High Energy Cosmic Ray flux. Several identified TeV gamma sources (e.g. Active Galactic Nuclei, SuperNova Remnants and Gamma Ray Bursts) are expected to be also high-energy neutrino sources. Neutrinos (ν) are, indeed, very promising astrophysical probes to explore the far Universe. Being light and uncharged leptons, neutrinos interact only “weakly” with matter and are not affected by electromagnetic interactions. These particles propagate through the Universe, straight and without losing their energy. They reach the Earth from astrophysical environments obscured to high-energy gammas and hadrons that, on the contrary, interact with the cosmic background radiation and with magnetic fields. In the last decade the “hunt” to cosmic neutrinos has become a major astroparticle physics activity, and neutrino astronomy is expected to open a new window on the “violent” Universe. Due to faintness of cosmic neutrino fluxes and difficulty in detecting the elusive neutrinos, theoretical estimates indicate that a detection area of the order of a few km^2 is required to measure High Energy (HE) cosmic ν fluxes. High Energy neutrinos are detected through deep-inelastic scattering of the ν with a target nucleon N. In the $\nu+NX\rightarrow l+X$ interaction, the lepton l escapes while the hadronic debris X leads to a hadronic cascade. The initial neutrino energy is shared among the lepton (70%$\div$80%) and the hadronic cascade (20%$\div$30%). In weak charged-current (CC) interactions the outgoing lepton is charged and it preserves the neutrino flavour (e, μ or τ). In neutral-current (NC) interactions, the outgoing lepton is a neutrino, and only the hadronic cascade is detectable. The detection of the ν interaction is, therefore, based on the observation of the outgoing charged lepton and/or of the hadronic cascade.

Due to the low νN cross section and to the faint expected astrophysical ν fluxes (flux $\propto E^{-2}$), neutrino detectors must have an interaction target mass of several GTons (for $E_\nu=10^{12}$ eV$\div$ 10^{16} eV) and much be much larger for higher energies. For this reasons natural media must be used as neutrino interaction targets. Depending on the energy range to explore, different experimental techniques were proposed (Fig. 1):

- in the range $E=10^{12}$ eV$\div10^{16}$ eV, the technique is based on the detection Cherenkov (UV-blue) light originated by relativistic charged leptons and/or hadrons outgoing a CC neutrino interaction. This technique efficiently works in water and ice;
- at higher energies, the proposed experiments rely on: the detection of radio pulses produced by e.m. showers following a neutrino interaction (in polar ice, salt domes or in the Moon regolith); the detection of acoustic waves produced by deposition of energy in the neutrino interaction (in seawater or in polar ice); the detection of air showers initiated by neutrinos interacting with rocks or deep Earth’s atmosphere.

The underwater/ice optical Cherenkov technique is widely considered the most promising experimental approach to build high-energy neutrino detectors in the $10^{12}\div10^{16}$ eV energy range. The quest for the construction of km^3-size detectors has

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doi:10.1016/j.nima.2012.01.052

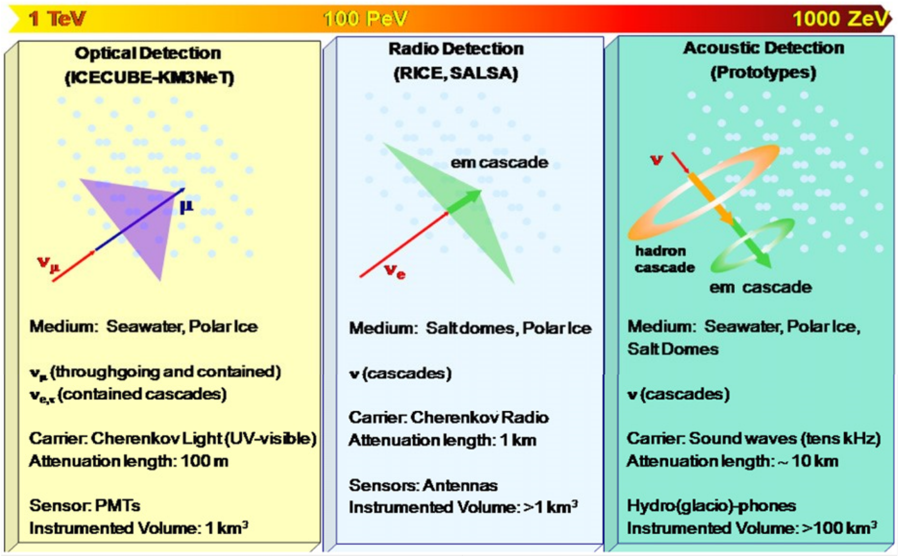

Fig. 1. Detection techniques for high-energy astrophysical neutrinos as a function of the ν energy range.

already started. At the South Pole the construction of the IceCube neutrino telescope (http://icecube.wisc.edu) is finished, while EU is endorsing the construction of the KM3NeT neutrino telescope in the Mediterranean Sea (http://www.km3net.org), born from the expertise acquired by the ANTARES (web page antares.in2p3.fr), NEMO (web page nemoweb.lns.infn.it) and NESTOR (web page http://www.nestor.org.gr) Collaborations. IceCube and the future KM3NeT are km^3-size arrays of several thousand optical sensors (photo-multiplier tubes), displaced in deep sea at an average distance of about 100 m, i.e. the attenuation length of blue light in clear waters. First experimental results from IceCube and ANTARES have already ruled out several optimistic models of abundant cosmic neutrino production, indicating the need for detectors larger than 1 km^3, like the ≈ 5 km^3-size KM3NeT under design. Available budget, due to PMT technology costs, limits to this value the achievable size of Cherenkov detectors. Astrophysical models and cosmic ray flux measurements suggest, however, that a flux of cosmic neutrinos is expected to arise from the interaction of ultra high-energy ($E > 10^{19}$ eV) protons, accelerated in powerful astrophysical sources, with the cosmic microwave background radiation. Greisen [8], Zatsepin and Kuzmin, [20] -hereafter GZK—described this phenomenon and these neutrinos are named GZK neutrinos. At these energies the expected neutrino flux is so low that km^3-scale Cherenkov detectors are too small to detect neutrino events. The thermo-acoustic technique was thus proposed to measure the GZK neutrino flux. The basic idea is that, following the interaction of a GZK neutrino in water, a large amount of the neutrino energy can be deposited in a small volume of water. This instantaneous water heating produces a bipolar acoustic pulse. The expected pulse spectrum is centred at about 30 kHz with a spread of few tens kHz. At these frequencies sound attenuation in seawater is small, and the expected pulse amplitude is about 100 mPa, for a 10^{20} eV neutrino, at 1-km distance from the vertex of the neutrino interaction. The expected number of such events is very small, few in 10 km^3 of water per year, for this reason their detection can only be achieved using large detectors (several tens km^3) made of sparse and poorly dense arrays of acoustic sensors (see contribution of R. Nahnhauer in this conference). These sensors are hydrophones, for water applications, or glacio-phones, for ice installations. Though the studies on acoustic technique are still in an early stage, its potential use to build very large neutrino detectors water is appealing, thanks to the optimal properties of water as sound propagator. The idea of acoustic neutrino detection, first proposed by Askaryan [5], is based on the reconstruction of hadronic and electromagnetic showers produced by neutrino interaction in dense media. As discussed above, both in the case of CC or NC interaction, the hadronic cascade carries about 25% of the neutrino's energy. The deposit of the cascade energy in a small volume of water, cylindrical in shape with a length of few tens of metres and a few centimetres in radius, turns out in heating of the medium, therefore in its expansion. According to theoretical works [11], the acoustic pulse is bipolar and the frequency spectrum of the signal has a typical maximum amplitude in the range of few tens kHz. The amplitude of the bipolar signal is $P \approx \Gamma E 10^{-19}$ [Pa/eV], where Γ is the dimensionless Gruneisen coefficient of the medium (calculated from medium thermodynamic properties, that is 0.12 in water). Since, at frequencies of few tens kHz, acoustic pulses can travel large distances in ice, seawater and salt, these natural media can be used to build large volume neutrino detectors instrumented with sparsely spaced arrays of acoustic sensors. The energy threshold for neutrino acoustic detection is set by the ratio between ambient noise and signal. In the frequency range of interest for neutrino detection ($10 \div 40$ kHz), the acoustic ambient noise amplitude in deep sea adds up about few mPa. This permits, in a first approximation, the discrimination of acoustic signals originated by neutrinos having $E > 10^{19}$ eV (assuming 1 km distance between source and detector). Sophisticated acoustic signal identification, based on matched filters, and reconstruction strategy of the acoustic wave-front geometry is required to improve detector sensitivity. Another intriguing possibility [16] is the use of a very large volume array of acoustic sensors both as independent acoustic detector and as a calorimeter for the few (but almost background free) UHE neutrino events detected by the future KM3NeT Cherenkov telescope. At energies greater than 10^{16} eV, the majority of neutrino-induced muon tracks, reconstructed by the km^3 optical telescope, are quasi-horizontal. For these events, the neutrino interaction vertex is located several km outside the telescope. Clusters of acoustic modules, displaced in a large volume around the km^3 telescope, could be able to identify the acoustic signature generated by the hadronic cascade at the vertex. Once the neutrino vertex is located, the muon range and its energy loss can be measured ($R_\mu \approx 4$ m/GeV), while the energy of the muon crossing the km^3 detector is reconstructed by the PMT array (see KM3NeT TDR). Despite the fact that, for independent acoustic detection, the neutrino energy threshold is high and in scarce overlap with the energy range accessible to Cherenkov detectors, the time and arrival direction correlation between optical and acoustic signals would help to strongly lower the acoustic detection energy threshold. An improvement of about one order of magnitude is expected using the information of the sound wave arrival direction, provided by the optical detector, to improve the acoustic signal to background ratio. At these energies only few events are expected over the lifetime of the KM3NeT detector, but their detection would be almost background free.

2. Experimental activities on acoustic neutrino detection in deep-sea: the role of Mediterranean Sea-based experiments

Research and development on this field were, to date, carried out using small subsets of military hydrophone arrays in intermediate depth waters (<1000 m depth), such as in the case of the SAUND [17] and ACoRNE collaborations [14], or as subsystems of existing infrastructures for neutrino astronomy in lake Baikal ([6]), and in the Mediterranean Sea: NEMO and ANTARES. In the framework of the activities of the ANTARES neutrino telescope, the AMADEUS (ANTARES Modules for Acoustic Detection Under the Sea) group has deployed few tens hydrophones onboard two strings. Hydrophones are both commercial piezo-ceramic hydrophones, self-made piezo-ceramic hydrophones and self-made hydrophones hosted in and acoustically coupled with 17″ pressure-resistant glass spheres [10] The system is operating continuously and automatically, requiring only little human intervention. AMADEUS allows for extensive studies of both transient signals and ambient noise in the deep sea, as well as signal correlations on several length scales and localisation of acoustic point sources. Thus the system is excellently suited to assess the background conditions for the measurement of the bipolar pulses expected to originate from neutrino interactions. The NEMO collaboration started studies on acoustic neutrino detection in 2003. The research was focused on the design, construction and operation of the NEMO-OνDE detector [15]: a small antenna of hydrophones aimed at measuring in real-time the acoustic noise spectrum (30 Hz $< f <$ 42 kHz) in deep-sea and, eventually, to detect and track acoustic sources. OνDE was successfully deployed and operated at the INFN deep-sea infrastructure offshore Catania [12]. Acoustic noise was studied as a function of time, weather conditions, presence of ships and biological sources, with large echo in neutrino telescope and bio-acoustics communities, as reported major science journals [13]. To study the response of a neutrino acoustic detector in situ it is also important to have a "calibrator" capable to generate the expected signal. The ACORNE group has developed a technique to produce a bipolar pulse shape with one acoustic transducer. The method involves characterising the transducers response via an equivalent circuit, tested by applying a known signal, and finally determining the required excitation pulse to create a bipolar acoustic pulse. Further studies have been carried out to estimate the number of coherent transmitters required, in a 10 m long volume of water, in order to accurately generate the expected pancake [18] Another approach developed by the ANTARES group in Valencia [3] uses the non-linear behaviour of media to produce a bipolar pulse with cylindrical wave front. Transducers are excited with two different MHz waves with a frequency difference equal to the desired one. The acoustic bipolar pulse amplitude is proportional to the squared input voltage applied to the transducer and confined in about 10 degrees in angle. The activities of the ANTARES and NEMO groups are today converging in common activities finalised to the development of acoustic sensors to be installed on board the KM3NeT detector (see the KM3NeT Technical Design Report at the web address http://www.km3net.org/tDR/KM3NeT-TDR.pdf). The KM3NeT telescope will be formed by about 300 mechanical structures (hereafter detection unit, DU). Twenty storey's compose each DU—the storey is a 6 m long rigid bar. The vertical distance between storey's is 40 m. Mechanical ropes interconnect stories, and an electro-optical backbone is used to transmit power and data. Two DOMs (digital optical modules) are mounted in each storey. The DOM consists of 32 Photomultiplier tubes glued on a 17″ glass housing and its read-out and data transmission electronics. The main purpose of acoustic sensors is to provide accurate positioning of the KM3NeT telescope detection units though acoustic measurements. A long-baseline (LBL) of acoustic transceivers, located in the seafloor, is used to triangulate positions of acoustic receivers (hydrophones or piezo-electric sensors glued on the DOM glass housing) installed on the detection unit mechanical structures (Fig. 2).

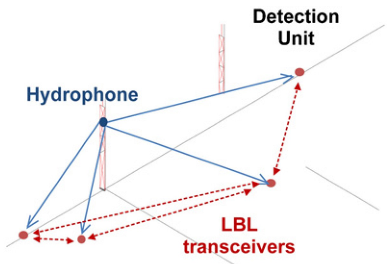

Fig. 2. Scheme of the KM3NeT acoustic positioning system. The LBL is a geo-referenced system to identify the positions of acoustic receivers on the DU. The system is based on measurements of acoustic time of flight between transceivers and hydrophones.

The LBL transceivers, connected to shore through electro-optical link, emit a calibrated acoustic signal, triggered by the detector master clock. Use of FFR (free flooded ring ceramic hydrophones) permits to obtain both optimal transmission and reception voltage response to build efficient LBL transceivers [4].

Acoustic receivers are installed on each storey of the detection unit. The hydrophone's analogue signals are digitised by a dedicated board at 192 kHz sampling frequency and 24 bit in amplitude and, then, sent to the so-called Central Logic Board (CLB). The latter is an FPGA-based electronic board that collects data from PMTs, acoustic sensors, and oceanographic probes. The CLB sends the continuous stream of acoustic data -embedded with PMT and oceanographic probes data- to shore, via optical fibre. In the shore laboratory acoustic data are parsed and addresses to a dedicated data analysis system. Both the acoustic receivers on the DU and the LBL transceivers are synchronous and phased with respect to the master clock time signal transmitted from shore. This set-up allows also to use of acoustic data for study of acoustic neutrino detection and search for acoustic and optical coincidences. It will also allow monitoring of the environment around the detector and studies of Earth and Sea Science: biology, geophysics and oceanography, as described in the following sections.

A major step towards the acoustic system of KM3NeT is now conducted with the installation of an array of 18 acoustic receivers installed on-board the NEMO Phase II detector (see contribution of F. Simeone in this conference), that will be deployed in the next months at the INFN deep sea infrastructure of Capo Passero, at 3500 m depth.

The array consists of 2 FFR, 2 piezo-electric sensors glued on glass housing and 14 high-sensitivity (-173 dB re 1 V/μPa) and broadband (10 Hz–70 kHz) hydrophones. All sensors are read by low-noise professional audio electronics and sampled at 24 bit/192 kHz [2]. The 14 broadband hydrophones form the Submarine

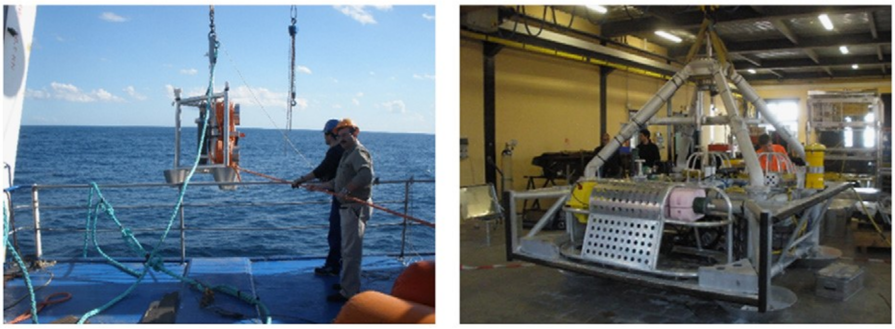

Fig. 3. Two LIDO stations ready for deployment at the INFN-LNS test site of Catania (2100 m water depth).

Multidisciplinary Observatory. Thanks to large size, the detector will efficiently reconstruct the acoustic source position allowing multidisciplinary studies.

3. Earth and sea science applications

Marine mammals, especially large cetaceans such as sperm and baleen whales, are well known endangered species. Research on cetaceans was mainly carried on with invasive or semi-invasive interaction with the animals, e.g. visual census and tissue recovery and analysis. In recent years bio-acoustics emerged as an optimal research methodology to detect and study cetaceans in their environment. Bio-acoustics relies in the analysis of typical acoustic signatures, used by of cetaceans for social communications, hunting, navigation and environment exploration, to detect their presence underwater, to count them and to count their movements. Arrays of piezo-electric acoustic sensors, towed by research vessels or deployed in autonomous mooring line, have been extensively and successfully adopted for cetaceans monitoring since the '90s. Bio-acoustic has, thus, provided a large improvement in marine mammals' research. These techniques however show, technological and scientific limits. Towed array, though sensitive, are operated for limited time during ship cruises and close to sea-surface, affected by wave noise and ship motion. Mooring lines suffer for limited recording time due to autonomous power supply and data storage. Acoustic antennas, anchored on sea-floor and connected via electro-optical cables to shore allow totally passive acoustic detection in low-noise conditions, continuous monitoring, and enable high-quality and large band-width data recording.

The long-term monitoring of the underwater acoustic world opens, therefore, new perspectives in the monitoring of marine mammal populations and of their trend in relation to human activities, such as the ship traffic, and its related noise, and to long-term changes of the environment like those driven by climate changes. Permanent underwater platforms are an invaluable instrument for monitoring the environment and for managing its conservation.

AMADEUS and OνDE demonstrated the potential of this novel technique recording acoustic signals in a wide range of amplitudes and frequencies. Acoustic noise and its variations were acquired and recorded providing, to date, one of the largest data archive of acoustic noise at these depths. Recorded data had a groundbreaking influence on the marine biologists community. OνDE discovered, since first recordings, biological sounds revealing marine mammals passing or living in the area. The detection of sperm whales was an especially exciting find. Biologists knew that whales travel through the whole Mediterranean Sea, the recordings provided evidence for record numbers of transiting whales and for a prolonged presence of them in the waters of Eastern Sicily [19].

Bioacoustics is a major task of the LIDO (Listening to Deep Ocean) demonstration mission of ESONET NoE (http://www.esonet-emso.org/esonet-noe/). The LIDO D.M. consists in the operation of a stand-alone observatory in the Cadiz Gulf (offshore Portugal) and a cabled observatory in the East-Sicily Node (off Catania, Italy). In particular, the LIDO-East Sicily installation represents a further major step within ESONET/EMSO: it is a fully integrated system for multidisciplinary deep-sea science, capable to transmit and distribute data in real time to the scientific community and to the general public. The LIDO-East Sicily node (see Fig. 3) will be soon deployed. It hosts a large number of sensors aimed at the monitoring and studying of oceanographic and environmental parameters, geophysical phenomena, ocean noise monitoring and identification and tracking of biological acoustic sources in deep sea. The latter item will be performed using two tetrahedral arrays of 4 piezo-electric hydrophones, located at a relative distance of about 5 km, and at about 25 km from the shore, connected with the two terminations of the deep-sea cabled infrastructure of Catania, owned and operated by INFN and INGV [12,9]. A prototype for Tsunami Early Warning System is also installed aboard the LIDO station offshore Catania: together with the geophysical and oceanographic sensors (gravimeter, scalar and vectorial magnetometers, 3-D current metre, Acoustic Doppler Current Profiler, Conductivity-Temperature-Pressure probes) the observatory will also measure amplitude and direction of low-frequency waves. New geophysical models [7] show, indeed, that tsunamigenic earthquakes produce low frequency ($f \approx 1$ mHz $\div$ 100 mHz) sound waves propagating in deep-sea. Due to faster propagation of acoustic waves ($c_s \approx 1550$ m/s) in sea-water with respect to the tsunami wave ($v \approx 50 \div 100$ m/s), the acoustic wave information could be used as an efficient indicator for the early tsunami alert systems.

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