Acoustic Detection

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Abstract. The proposal of acoustic neutrino detection is living a renaissance: the interest in ultra high energy neutrino detection, the fast improvements of deep sea technology and the availability of large deep sea research infrastructures are the three main ingredients to explain the new interest in this technique. The status of simulation work, medium studies, sensor developments and first results from test experimental setups are presented.

1. Introduction

The astrophysics and particle physics community is addressing its efforts in the realization of large experimental apparatuses for the detection of high energy neutrinos originated in cosmic sources or produced in the interaction of Ultra High Energy Cosmic Rays (UHECR) with the Cosmic Microwave Background Radiation, i.e. the GZK neutrinos [1]. Though there is not indication of neutrino sources yet, the sensitivity of the existing apparatuses is rapidly reaching the level of the Waxman-Bahcall limit [2], that is the conservative limit on HE neutrino flux assuming hardronic acceleration and beam dump in cosmic sources. The required size of these apparatuses is about 1 km^3 for neutrinos of energy $10^{12} \div 10^{15}$ eV and larger for more energetic neutrinos. Moreover the detectors must be placed at large depth (about 3000 m.w.e.) to shield the detector from the intense background of cosmic particles that would wash out the neutrino signal. Three experimental techniques were proposed to identify the high energy cosmic neutrino signatures: the detection of Čerenkov light originated by muons following a CC neutrino interaction in sea/lake-water or polar ice [3, 4]; the detection of acoustic waves produced by deposition of energy in the interaction of ν in sea/lake-water, polar ice or salt domes [5]; the detection of radio pulses produced by e.m. showers following a neutrino interaction in polar ice or salt domes [6].

2. The Thermo-acoustic technique

The idea of acoustic neutrino detection, first proposed by Askaryan in 1957, is based on the fact that when an UHE neutrino interacts in a suitable medium such as ice, water or salt, originates a hadronic shower that carries about 25 percent of the neutrinos energy. The quasi-instantaneous deposit of this energy in a small volume of water, cylindrical in shape with a length of few tens metres and a few centimetres in radius, results in heating of the medium thus in an expansion. Acoustic pulses from particle showers were first observed at Brookaven NL in 1979 [7], using a beam of 200 MeV protons with a total energy deposit in water of about 10^{18} eV. The pulse amplitude as a function of total energy deposition, water temperature and pressure was studied. According to Learned's paper [8], the resulting acoustic pulse is bipolar, following the second

time derivative of the temperature of the medium, with a frequency which is dominated by the transverse spread of the shower, with maximum amplitude in the range of few tens kHz. At these frequencies acoustic pulses can travel large distances in a medium such as ice, water or salt. This leads to the prospect of potentially huge effective volume neutrino detectors being built from relatively sparsely spaced arrays of acoustic sensors. The amplitude of the bipolar signal is proportional to the deposited energy and related to the medium properties: the thermal co-efficient of expansivity (β), the sound velocity (c_s) and the specific heat capacity (C_p). Due to the instantaneous and coherent energy deposition along the shower axis, co-linear with the neutrino direction, the pulse is "pancake-shaped" and it propagates, in a homogeneous medium, perpendicularly to the neutrino direction. The acoustic pulse production was recently confirmed by several experiments, using proton beams (in Uppsala and ITEP Moscow) and high intensity laser beams (in Erlangen). A rule of thumb to calculate the acoustic pulse amplitude produced by a neutrino of energy E_ν, impinging in a dense medium is $p_{max} \simeq 0.25 \times E_\nu \times \Gamma \simeq 6 \cdot E_\nu$ Pa/eV; where $\Gamma = c_s^2\beta/C_p$ is the Gruneisen coefficient of the medium. The Γ coefficient for deep Mediterranean Sea water is about 0.12, about a factor ten larger in polar ice and about 3.2 in compact mineral salt. Thus the pulse amplitude produced by a $E_\nu = 10^{20}$ eV neutrino, recorded at 1 km distance, is expected to be about 0.5 Pa in water and 5 Pa in ice, neglecting sound losses.

3. Study of medium properties

As shown before, the Gruneisen coefficient is a useful parameter to evaluate the expected neutrino acoustic pulse. However the approximation of large natural media as homogeneous media is not correct and real acoustic properties of different media must be taken into account. Seawater is a well known medium, thanks to several military and industrial studies on sound propagation and reliable numerical codes, with detailed description of sound propagation in water, are available. In the frequency range interesting for neutrino detection, the sound absorption coefficient in seawater is $a(f) \simeq 10^{-2} f^2_{10kHz}$ dB/km, that leads to an absorption length of about 10 km at $f = 10$ kHz. Sound velocity changes as a function of temperature, salinity and pressure (depth), therefore sound wave diffraction must be taken into account. At shallow depth salinity and temperature dominates the sound speed profile, at large depth pressure is the dominant parameter ($\Delta c_s/\Delta z \simeq 1.65$ cm/s/m). The net effect is that the expected pancake-shaped neutrino-induced wavefront becomes a hyperboloid in the real case. Another fundamental parameter for the study of the acoustic technique is the knowledge of the acoustic background in deep sea. Contrary to the usual definition of "kingdom of silence", seawater is now known as a noisy environment. Noise in deep sea varies as a function of time and, in the frequency range of interest, is mainly due to: surface agitation, biological sources and human-operated instrumentations (sonars, airguns, pingers,...). The former is responsible for a diffuse background and it is well described, at shallow depth, by the Knudsen's relation [9]: $SPD(f_{Hz}, SS) \simeq 94.5 - 10\ log f^{5/3} + 30\ log(SS + 1)$ dB re μPa^2/Hz; where SPD is the sound pressure density and the sea state parameter SS indicates the surface agitation in a scale from 1 to 10. Marine mammals, shrimps and human noise produce impulsive loud sounds and a diffuse background that may also wash out the expected neutrino signal. Most of the noise measurements reported in literature were carried out to shallow depth. In recent years the possibility to use military or new scientific infrastructure (built for Cherenkov neutrino telescopes) gave the possibility to measure acoustic noise in deep sea to experimental groups: NEMO-OνDE [10], ANTARES-AMADEUS [11], ACORNE [12] and SAUND [13].

Though ice shows a larger Gruneisen parameter, the acoustic properties of ice are still not well understood. The SPATS [14] group is conducting measurements in deep polar ice at the installation site of the IceCube detector; sound velocity and absorption length were theoretically evaluated to be respectively $c_s \simeq 3850$ m/s and $L_a \simeq 800$ m at 2000 m depth. Measurements,

difficult due to the not perfectly known behavior of acoustic sensors in deep and cold polar ice, indicate a good agreement with the estimated c_s, while the determination of L_a is still uncertain. The noise measurements indicate a decrease of noise amplitude as a function of depth and a Gaussian distribution of amplitudes in deep ice. Another medium of interest for acoustic detection is the permafrost, the thick layer of firn and frozen compounds that covers large regions of Northern Siberia. Askaryan first proposed the use of permafrost and recent measurements indicate it as a suitable medium with $c_s \simeq 4000$ m/s and excellent sound propagation properties below 60 kHz.

4. Studies for a Future Large-Scale Acoustic Detector

The study of performances of future acoustic neutrino detectors is conducted by several groups. This requires a reliable description of particle physics processes, of the sound production and propagation in the medium, of the sound detectors response and the implementation of strategies for event triggering and reconstruction.

The common approach for the simulation of neutrino-induced shower in water or ice is to consider the neutrino interaction, using either the cross section from Ghandi et al. [15] or reliable codes such as ANIS [16]. The hadronic shower (and the electromagnetic one in the case of ν_e interaction) development is then simulated using custom codes or implementing high energy processes (e.g. LPM) in GEANT [17]. A further step was recently conducted by the ACORNE collaboration that modified the CORSIKA [18] software suite, which is used to generate UHE cosmic ray showers in the atmosphere, to generate UHE neutrino interactions in water. The aim is the development of a "all-processes-in" software tool and the reduction of long calculation time required for UHE events. Extensive crosschecks against GEANT and other software tools have been made demonstrating the reliability of the code, with deviation of few percent in the determination of energy loss longitudinal and radial profile compared to the full simulations. Once the shower energy density deposition in the medium is calculated, the acoustic pulse can be simulated as a function of distance and time using the Learned's approach. It is important, at this stage, to take into account the medium properties to correctly simulate the pulse amplitude and the wavefront geometry as a function of distance from the shower.

Due to the faintness of neutrino fluxes at extreme energies, neutrino acoustic detectors are thought as an array of several thousand acoustic sensors, displaced randomly or in ordered detection units, within a huge volume of water (about 1000 km^3). As reported in calculation performed by the AMADEUS group [19], if one considers an array of randomly sparse sensors, the effective volume ($V_{eff} = N_{det}/N_{gen}V_{gen}$) for $E_\nu = 10^{20}$ eV may reach about 100 km^3 for a detector made of about 200 sensors per km^3 with not much gain for higher densities. Taking into account sound refraction, seawater water boundary conditions and a threshold adapted to different sea conditions [20] the expected sensitivity for a 1500 km^3 detector, instrumented with 200 hydros per km^3 could reach the WB Limit for $E_\nu = 10^{20}$ eV neutrinos. A different approach was recently proposed by the ACORNE group that simulated the response of an array of 1100 modules displaced in 1 km^3 volume of water, shown in left-hand side of figure 1 [12]. The use of sophisticated signal identification and reconstruction strategies based on matched filters and wavefront geometry, may allow to reach a sensitivity below the Waxman-Bahcall limit for UHE neutrinos: the lowest curve represents the sensitivity for 10 years data acquisition, threshold 5 mPa, at 90% CL).

Thanks to the possibility to use also the radio Cherenkov technique in ice, the SPATS group has simulated a possible hybrid detector made of: 80 IceCube strings plus an external ring of 13 strings deployed in holes at 1 km distance from the centre (2.5 km deep); 91 radio/acoustic strings with a spacing of 1 km, 1.5 km deep. Sixteen events per year could be seen by the acoustic detector, and 8 in coincidence with the radio detectors: that would offer the potential for cross-calibration of signals from the different technologies 1.

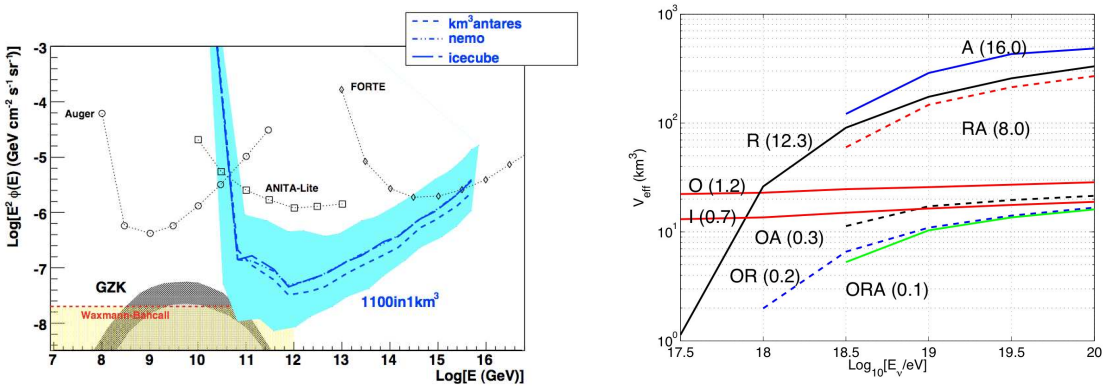

Figure 1. Left: expected sensitivity for an acoustic neutrino detector of 1 km^3, for different regular detector geometries and a random geometry (cyan area) [12]. Right: Effective volume and expected events in a optical-radio-acoustic neutrino telescope at the South Pole [14].

5. Technological R&D: sensors and calibrators

The most widely used acoustic sensors for water (hydrophones) are piezo-electric ceramic gauges, moulded in water-tight resins, commercially available but typically used for shallow water and short term measurements. Acoustic neutrino detection requires special hydrophone productions and the correct determination of the sensor calibration curve as a function of depth, that is rarely required for commercial applications. For this reason the NEMO Collaboration is developing together with NURC (Nato Undersea Research Centre) a facility to test and calibrate hydrophones, in amplitude and phase, under high pressure in water. This permits the test and the selection of ceramics having sensitivity (i.e. the ratio between input pressure and output voltage) independent on pressure. Some groups also considered the development of custom acoustic sensors, matched to the expected bipolar acoustic signal in order to reduce the costs of a future large volume acoustic array [11]. The design of these hydrophones requires a good theoretical microscopic understanding of the piezoelectric sensors and its coupling. Acoustic sensors for deep ice (glaciophones) were built by the SPATS team are made of 3 piezo-ceramics glued inside a metallic cylindrical vessels. The measured sensitivity in low pressure environment is promising -114 dB re V/μPa, however their response in deep and cold ice requires further investigation. A different approach is the development of optical fibers hydrophones carried out independently by two groups of INFN. Pressure is measured with Mach-Zender interferometry in one case or measuring the optical signal attenuation of a fiber coil. Preliminary results are promising, beng the latter technique more advanced but characterised by a frequency upper limit of about 10 kHz.

To study the response of a neutrino acoustic detector *in situ* it is also important to have a "calibrator" capable to reproduce 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 10m long volume of water, in order to accurately reproduce the expected pancake. Another approach, developed by the ANTARES group in Valencia [21], uses the non linear behavior of media to produce a bipolar pulse with cylindrical wavefront. 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.

6. Pilot experiments

In order to test and develop technologies for future acoustic neutrino detectors, different groups have constructed dedicated small-scale apparatuses or used existing military arrays to acquire acoustic signals in deep sea or ice. The South Pole Acoustic Test Setup (SPATS) team aims at R&D and tests for the construction of a large acoustic detector to complement IceCube. Three lines, each equipped with 7 transmitters and 7 receivers per line, were deployed within the IceCube detector. Hydrophone digitization is performed at surface using 200/400 kHz ADCs. The array permitted the first studies of deep ice acoustic properties, using calibrated pingers deployed at several depths and distances. The next steps foresees the test of new hydrophones and further calibration runs with calibrated pingers. The SAUND (Study of Acoustic Ultra-high energy Neutrino Detection) collaboration uses the AUTEC naval array of wide band hydrophones deployed at $\simeq$ 1500m depth offshore Bahamas. SAUND recorded 15 days of data reading out 6 hydrophones at the site, displaced in a $\simeq 7$ km^2 wide area and obtained the first limit of the UHE neutrino using the acoustic technique [22]. In the second phase of SAUND, data from 56 hydrophones, covering an area of about 1000 km^2 were recorded for 120 days, aiming at reaching 1 year of data acquisition. SAUND phase 2 is currently active and is also permitting a detailed characterisation of deep sea noise as a function of frequency and direction. The Baikal collaboration has undergone several acoustic related initiatives in parallel with the operation of the underwater Cherenkov detector. A module equipped with four hydrophones was deployed: the lake noise was measured and a number of bipolar-pulses were recorded and studied as a function of amplitude and arrival direction [**?**]. A sting array of hydrophones was also deployed, to study acoustic pulses in coincidence with shower recorded by the array of scintillators installed on the lake surface [**?**]. The ACORNE (Acoustic Cosmic Ray Neutrino Experiment) collaboration has access to a military array of hydrophones situated at about 250 m depth, off the coast of Rona in North West Scotland. Eight hydrophones were instrumented and read out continuously at 140 kHz sampling rate for two weeks in 2005 and several weeks in 2006. Data have been analysed using a number of signal processing techniques to identify possible neutrino-like candidates. Average noise spectra for all eight hydrophones have been measured and the effect of biological activity is under study. 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 (see figure 2), self-made piezo and self-made hydrophones hosted in and acoustically coupled with 17 pressure-resistant glass spheres that currently house the ANTARES PMTs. The system permitted the monitoring of deep sea noise in the site and the identification of acoustic signal emitted by the beacon used for the ANTARES acoustic positioning system. The NEMO Collaboration is also conducting the first studies for acoustic neutrino detection. In 2005 the Collaboration deployed OνDE (Ocean Noise Detection Experiment) at the NEMO test site, 2000 m depth, 25 km off the coast of Sicily. OνDE, that was successfully recovered on April 2008, comprises four hydrophones arranged on a pyramidal-shaped mounting and low-cost electronics for data acquisition and transmission 2. All data, sampled at 96 kHz and 24 bits, were transmitted in real-time and recorder for 5 minutes every hour. Noise was studied as a function of time, weather conditions, presence of ships and biological sources with important drawbacks in bioacustics [25]. Based on the experience of OνDE the collaboration is now focuses in the realization of an innovative acoustic position system for the NEMO phase II detector [4]: a vertical array of 34 hydrophones, 750 m high, that will be also used as an underwater acoustic detector.

7. Conclusions

In the last few years, significant progress has been made in the field of acoustic neutrino detection. Reliable and fast simulation codes for UHE neutrino interaction and shower propagation were

Figure 2. Left: an acoustic module of AMADEUS, equipped with 6 hydrophones. Right: OνDE before the deployment.

developed and acoustic pulse production and propagation codes are available for different media. Different groups are conducting studies to characterize acoustic properties of deep seawater and ice and developing the required technologies (sensors, calibrators, electronics,...) for deep water/ice acoustic arrays. Test experiments were carried out using military arrays of hydrophones or available scientific infrastructures and first searches for neutrino signals were performed. The further step, i.e. the deployment of large acoustic arrays to complement underwater/ice neutrino telescopes, is under realization in IceCube with the SPATS project; while the possibility to use a large array of hydrophones in connection with the future Mediterranean neutrino telescope (KM3Net [4]) is under study.

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