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Acoustic Detection of Neutrinos: Review and Future Potential

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Abstract

The acoustic neutrino detection technique is a promising approach for future large-scale detectors with the aim of measuring the small expected flux of cosmogenic neutrinos at energies exceeding 100 PeV. The technique is based on the thermo-acoustic model, which implies that the energy deposition by a particle cascade—resulting from a neutrino interaction in a medium with suitable thermal and acoustic properties—leads to a local heating and a subsequent characteristic pressure pulse that propagates in the surrounding medium. The main advantage of using sound for the detection of neutrino interactions, as opposed to Cherenkov light, lies in the much longer attenuation length of the former type of radiation: several kilometres for sound compared to several ten metres for light in the respective frequency ranges of interest in sea water. As detection media for future detectors, water, ice, salt domes and permafrost have been discussed, but it is the first two which have been investigated most thoroughly by using existing arrays of acoustic receivers—mainly military arrays in various bodies of water—or by implementing dedicated acoustic arrays in Cherenkov neutrino telescopes. Such arrays have been installed in IceCube at the South Pole, in the Lake Baikal experiment in Siberia and in ANTARES and the former NEMO experiment in the Mediterranean Sea. The future KM3NeT neutrino telescope to be installed in the Mediterranean Sea will be equipped with acoustic sensors for position calibration that are suited to also serve acoustic detection purposes. Ongoing experiments in water and ice have established the feasibility of the acoustic neutrino detection technique and allowed for the investigation of prevailing background conditions. Methods to improve the signal detection efficiency and to reduce the rate of misidentified neutrinos have been devised and potential future large-scale detector designs are investigated using detailed simulations in combination with the wealth of collected experimental data. In this presentation, a brief review of acoustic particle detection, considering both theoretical and experimental aspects, will be given. The current status and plans for the future will be discussed.

1. Introduction

In 1957 G.A. Askaryan pointed out that ionisation and cavitation along a track of an ionising particle through a liquid leads to hydrodynamic radiation [1]. In the 1960s, 1970s and 1980s, theoretical and experimental studies have been performed on the hydrodynamic radiation of beams and particles traversing dense media [2, 3, 4, 5, 6, 7, 8]. One widely discussed application of this effect is the detection of ultra-high energy ($E \gtrsim 10^{18}$ eV) cosmic, i.e. astrophysical neutrinos. An isotropic flux of such neutrinos is expected from the interaction of cosmic rays of the highest energies with the photons of the cosmic microwave background [9].

While the acoustic detection of such neutrinos in salt domes [10, 11] and in permafrost [12] has also been discussed, water and ice are the media in which investigations of the method have been pushed the furthest. In the 1970s this idea was discussed within the DU-

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MAND[1] optical neutrino detector project [13] and has been studied in connection with Cherenkov neutrino detector projects since. The detection of ultra-high energy neutrinos is considerably more challenging than the search for high-energy neutrinos ($E \gtrsim 10^{10}$ eV) as currently pursued by under-ice and under-water Cherenkov neutrino telescopes [14, 15, 16]. Due to the low expected fluxes, volumina exceeding $100\,\mathrm{km}^3$ need to be monitored for interactions [17]. However, the properties of the acoustic method allow for sparsely instrumented arrays with $\sim$100 sensors/km^3.

This article concentrates on the acoustic detection of neutrinos in water. In Sec. 2, the detection method will be discussed in some more detail. In Sec. 3 an overview of current test setups for the investigation of acoustic neutrino detection techniques in water and ice is given and in Sec. 4 some recent results and current activities are presented. Planned activities in the context of the future KM3NeT neutrino telescope in the Mediterranean Sea will be discussed in Sec. 5 before in Sec. 6 conclusions and an outlook are given.

2. Acoustic Detection of Neutrinos

Neutrinos interacting with the nuclei of water molecules are producing hadronic particle cascades. The resulting energy deposition in a cylindrical volume of a few centimetres in radius and several metres in length leads to a local heating of the medium which is instantaneous with respect to the hydrodynamic time scales. This temperature change induces an expansion or contraction of the medium depending on its volume expansion coefficient. According to the thermo-acoustic model [2, 3], the accelerated expansion of the heated volume—a micro-explosion—forms a pressure pulse of bipolar shape which propagates in the surrounding medium. A frequently used expression for the pressure deviation p' from the static pressure as derived e.g. in [2] is

$$p'(\vec{r}, t) = \frac{1}{4\pi} \frac{\alpha}{c_p} \int_V \frac{\mathrm{d}V'}{|\vec{r} - \vec{r}'|} \frac{\partial^2}{\partial t^2} \epsilon(\vec{r}', t') \qquad (1)$$

with the bulk volume expansion coefficient α, the specific heat c_p and the energy deposition density ϵ of the particle cascade. The integral extends over the volume of the energy deposition. The signal amplitude p' can be shown to be proportional to the dimensionless quantity $v_s^2\,\alpha/c_p$, the Grüneisen parameter, when solving Eq. (1) for the case of an instantaneous energy deposition. Here v_s is the adiabatic speed of sound in the medium.

The coherent superposition of the elementary sound waves, produced over the volume of the energy deposition, leads to a propagation within a flat disk-like volume (often referred to as *pancake*) in the direction perpendicular to the axis of the particle shower. After propagating several hundreds of metres in sea water, the pulse has a characteristic frequency spectrum that is expected to peak around 10 kHz [18, 19, 20]. As the attenuation length in sea water in the relevant frequency range is about one to two orders of magnitude larger than that for visible light, a potential acoustic neutrino detector would require a less dense instrumentation of a given volume than an optical neutrino telescope.

3. Test Setups for Acoustic Neutrino Detection

Current or recent test setups for acoustic neutrino detection have either been add-ons to optical neutrino telescopes or have been using acoustic arrays built for other purposes, typically for military use. In the context of the DUMAND experiment, ideas about adding a large scale acoustic detector to a deep-sea optical neutrino telescope were already considered in the 1970s [13]. As the DUMAND experiment was not realised beyond a prototype phase, acoustic particle detection was subsequently pursued by the parasitic use of military arrays. In an early effort starting in 1997 by the SADCO[2] collaboration, a Russian Navy stationary antenna near Kamtchatka consisting of 2400 hydrophones was used for acoustic particle detection studies [21]—see also [22] and references therein.

Experiments in salt water, fresh water and ice that are currently taking data or are preparing to take data in the near future are discussed below in some more detail.

The **SPATS (South Pole Acoustic Test Setup)** project [23, 24], deployed up to a depth of 500 m in the upper part of four boreholes of the IceCube Neutrino Observatory, has continuously monitored the noise in Antarctic ice at the geographic South Pole since January 2007. As acoustic properties, in particular the absorption length and the speed of sound, have been subject to fewer experimental studies for ice than for water, these properties have been investigated with SPATS [25, 26]. Based on 8 months of observation, a limit on the neutrino flux above 10^{11} GeV has been

[1] Deep Underwater Muon and Neutrino Detection

[2] Sea Acoustic Detector of Cosmic Objects

derived [27], see Fig. 1.

In **Lake Baikal**, an antenna consisting of four hydrophones in a tetrahedral arrangement with equal interspacings of the hydrophones of 1.5 m has been placed at 150 m depth [28].

Conditions in Lake Baikal are not particularly favourable for acoustic neutrino detection, since in the deep zone of the lake the water temperature is only 1.5 − 2°C higher than that for the maximum density at the respective depth [29, 30]. The thermal expansion coefficient hence is close to zero and the Grüneisen parameter small. On the other hand, fresh water has the advantage over sea water in that the attenuation length is roughly one order of magnitude larger in the frequency range of 10 kHz to 100 kHz. In the context of the Gigaton Volume Detector (GVD) in Lake Baikal [31], an extension of acoustic detection efforts is planned, significantly increasing the number of hydrophone antennas.

At the **KM3NeT-Italia** site of the future Mediterranean neutrino telescope KM3NeT, which will be discussed in more detail in Sec. 5, it is planned to deploy 24 KM3NeT *strings* until 2016 in 3500 m depth, about 90 km offshore Capo Passero on Sicily. In addition, the installation of eight so called *towers* is planned, each one formed by a vertical arrangement of 14 horizontal bar structures or *floors* of 8 m length. Each bar structure is rotated by 90° with respect to those above and below, interconnected by ropes at 20 m vertical distances. Both towers and strings are equipped with photomultipliers for the optical detection of neutrino interactions. In addition, each tower will hold 29 hydrophones (one at each end of each bar and one at the anchor of the tower structure on the sea bed) that can be used for both acoustic position calibration and neutrino detection. This makes the setup an ideal testbed for acoustic neutrino detection on an intermediate scale between existing setups and long-term prospectives such as KM3NeT.

A predecessor project, the **OνDE (Ocean noise Detection Experiment)** project at the site of the NEMO[3] Cherenkov neutrino detector [32] has performed long term noise studies at 2050 m depth, 25 km east of Catania (Sicily) in the Mediterranean Sea at the location 37°30.008'N, 15°23.004'E. Phase I operated from January 2005 until November 2006. It employed 4 hydrophones forming a tetrahedral antenna with side lengths of about 1 m. In an analysis carried out with data recorded during 13 months between May 2005 and November 2006 [33], the average acoustic sea noise in the band 20 kHz to 43 kHz was measured as 5.4 ± 2.2 (stat) ± 0.3 (sys) mPa (RMS).

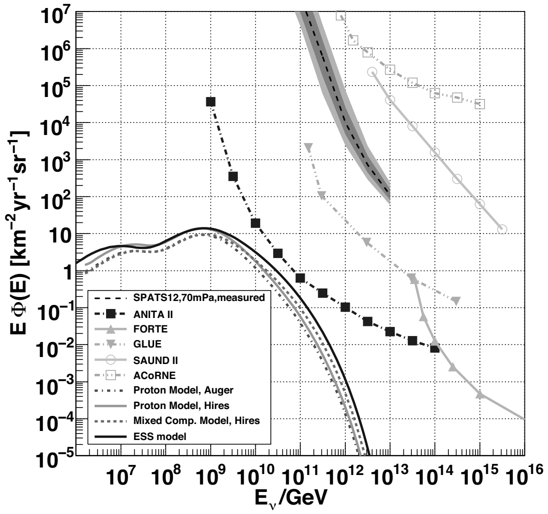

Figure 1: The neutrino flux limit of the 2009 SPATS configuration (70 mPa threshold, ≥ 5 hits per event) from [27]. The dark grey band (50 to 100 mPa threshold) around the limit considers uncertainties in absolute noise. The even broader light grey band includes additional uncertainties due to the choice of different acoustic models. Experimental limits on the flux of ultra-high-energy neutrinos are from ANITA II [34], FORTE [35], GLUE [36], SAUND II [37], ACoRNE [38]. Different models for the cosmogenic flux are shown [17, 39]. Figure adapted from [27].

The **ACoRNE (Acoustic Cosmic Ray Neutrino Experiment)** project [40] utilises the Rona hydrophone array, situated near the island of Rona between the Isle of Skye and the Scottish mainland. At the location of the array, the sea is about 230 m deep. The ACoRNE Experiment uses 8 hydrophones, anchored to the sea bed and spread out over a distance of about 1.5 km. Six of these hydrophones are approximately in mid-water, one is on the sea bed while the last one is about 30 m above the sea bed. The ACoRNE collaboration has derived a flux limit on ultra-high energy neutrinos [38] which is shown in Fig. 1.

The **AMADEUS (ANTARES Modules for the Acoustic Detection Under the Sea)** project [41] was conceived to perform a feasibility study for a potential future large-scale acoustic neutrino detector in the Mediterranean Sea. For this purpose, a dedicated array

[3]Neutrino Mediterranean Observatory

of acoustic sensors was integrated into the ANTARES[4] neutrino telescope [15]. The detector is located in the Mediterranean Sea at a water depth of about 2500 m, roughly 40 km south of the town of Toulon at the French coast at the geographic position of 42°48′ N, 6°10′ E. ANTARES was completed in May 2008 and comprises 12 vertical structures, the *detection lines*. Each detection line holds up to 25 *storeys* that are arranged at equal distances of 14.5 m along the line. A standard storey holds three *Optical Modules*, each one consisting of a photomultiplier tube inside a water-tight pressure-resistant glass sphere. A 13th line, called the *Instrumentation Line (IL)*, is equipped with instruments for monitoring the environment. It holds six storeys.

Within the AMADEUS system [41], acoustic sensing is integrated in the form of *acoustic storeys* that are modified versions of standard ANTARES storeys, in which the Optical Modules are replaced by custom-designed acoustic sensors. Dedicated electronics is used for the amplification, digitisation and pre-processing of the analogue signals. Six acoustic sensors per storey were implemented, arranged at distances of roughly 1 m from each other. The AMADEUS system comprises a total of six acoustic storeys: three on the IL and three on the 12th detection line (Line 12). In April 2013, the IL was re-deployed at a new position at 150 m distance from Line 12. Until then, the distance between the two lines was 220 m. The vertical distances between the two topmost acoustic storeys on the IL is increased from the standard of 14.5 m to about 110 m.

4. Acoustic Neutrino Detection: Current Activities

Most recent results from ongoing acoustic neutrino detection test sites have been presented by the AMADEUS and Lake Baikal acoustic arrays [42]. Both setups are too small to yield competitive limits on the flux of cosmic neutrinos so that the activities are mainly directed towards assessing the potential of future large scale setups, namely GVD in Lake Baikal and KM3NeT in the Mediterranean Sea. For this purpose, transient and ambient noise at the site of the installation have to be investigated. The ambient noise is broadband and is mainly caused by agitation of the sea surface [43], i.e. by wind, breaking waves, spray, and cavitations. Thus it is correlated to the weather conditions, mainly the wind speed, see e.g. [44]. It is predominantly the ambient background that determines the energy threshold for neutrino detection. Transient noise signals have short duration and an amplitude that exceeds the ambient noise level. These signals can mimic bipolar pulses from neutrino interactions. In the Mediterranean Sea, transient noise is relatively strong and can stem from marine mammals or anthropogenic sources, such as shipping traffic. In particular dolphins emit short signals with a spectrum similar to that of acoustic emissions from neutrino interactions. Experience from the data taken with the AMADEUS setup has shown that several stages of signal classification are needed for the suppression of ambient background. Machine learning algorithms have been used to identify bipolar pulses and to discard "clustered" events, which show a temporal and spatial correlation that is consistent with a moving source such as a ship or a sea mammal. However, even after these cuts, the remaining event density is still approximately 100 events/km^3/yr [45]. Further reduction requires larger detector structures and will be discussed in Sec. 5.

Both the Lake Baikal and the AMADEUS group use Monte Carlo simulations of neutrino interactions based on [18, 19]. As an example, Fig. 2 shows the simulated density of the energy deposition of a 10^{10} GeV hadronic shower, projected into the xz-plane. The z- and x-coordinates denote the directions along the shower axis and a direction orthogonal to the shower axis, respectively. Simulations of the resulting pressure pulses

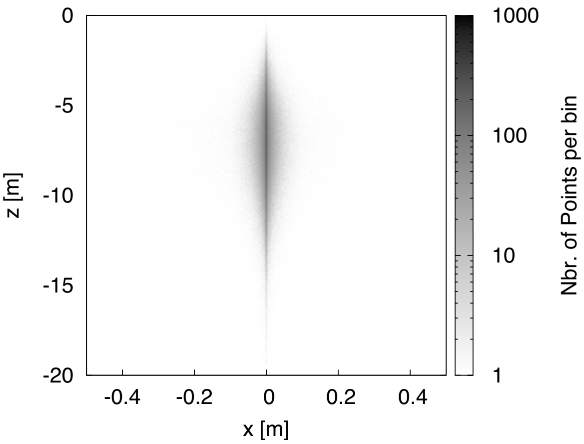

Figure 2: Density of the energy deposition of a 10^{10} GeV hadronic shower resulting from a neutrino interaction, projected from a three-dimensional distribution upon the xz-plane. Bin sizes are 0.01 m in x and 0.1 m in z.

at the positions of the hydrophones, together with simulations of the measured ambient noise background allow for the determination of flux limits and—ultimately—the measurement of a flux of ultra-high-energy neutrinos.

[4]Astronomy with a Neutrino Telescope and Abyss environmental Research

In the ongoing search for acoustic signals from neutrino interactions at Lake Baikal, no high energy neutrino candidates so far have been found. Investigations indicate the feasibility of neutrino detection with GVD with a threshold energy as low as 10^{19} eV [42].

As the transient background at the ANTARES site makes the search for neutrino signals much more difficult, activities concentrate on studies to be done with KM3NeT. This will be discussed in the following section.

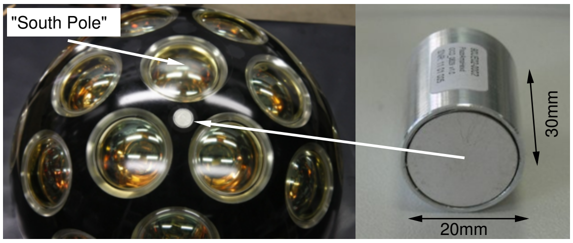

Figure 3: Acoustic piezo sensor for installation inside a KM3NeT optical module (right) and an optical module with installed sensor (left).

5. Future Activities in KM3NeT

5.1. The KM3NeT Detector

The KM3NeT detector will comprise a huge number of pressure-resistant glass spheres, the *optical modules*, each containing 31 three-inch-photomultiplier tubes (PMTs) together with their readout electronics [46]. A total of 18 optical modules will be distributed equidistantly along flexible strings of about 700 m length, one end of which is fixed to the sea floor and the other end is held taught by submerged buoys. These strings constitute a modular structure and when fully implemented, KM3NeT will eventually consist of several hundreds of such strings installed at three different sites, namely offshore Toulon (France), Capo Passero (Italy) and Pylos (Greece). In order to determine the relative positions of the optical modules with a precision of not worse than 20 cm, the detector will be equipped with an acoustic positioning system[5]. The system employs acoustic transceivers on the sea floor and acoustic receivers (hydrophones) in each storey. By performing multiple time-delay measurements and using these to triangulate the positions of the individual hydrophones, the hydrophone positions can be reconstructed relative to the positions of the emitters.

The KM3NeT positioning system is based on experience of the systems developed for ANTARES and the former NEMO experiment, see [47, 48] and references therein. Sampling will be done at about 200 k samples per second and all data will be transmitted to shore. This way, algorithms for the position calibration running on an on-shore computer farm can be adapted to in-situ conditions that may affect the shape of the received signal. Furthermore, the data can be used for additional analyses, in particular acoustic detection of neutrinos, or marine science investigations.

[5]The required precision is determined by the pointing resolution for point sources.

Custom designed acoustic sensors, based on the piezo-electric effect, will be used. These are compact units of a piezo ceramic and a preamplifier, glued to the inside of the glass sphere of the optical module near its "South Pole" (Fig. 3). The advantages w.r.t. standard external hydrophones are lower costs and a reduction of the number of failure points: no additional cables and junctions are required and the sensor is not exposed to the aggressive environmental conditions. Disadvantageous on the other hand is a reduced angular acceptance and the vulnerability of the system to electric interferences with the PMTs in the same sphere. Prototypes of the optical module were deployed in April 2013 at the ANTARES site [49] and in May 2014 offshore Capo Passero at the KM3NeT-Italia site. The data from the piezo sensors comply with the expectations, i.e. the operation of the PMTs increases the intrinsic noise, but the signals from the acoustic transceivers of the positioning systems at the respective sites are clearly detectable. Measures have been taken to reduce the interference of the PMT operation with the piezo sensors.

5.2. Acoustic Neutrino Detection within KM3NeT

A simulated neutrino signal for the string configuration of KM3NeT-Italia is shown in Fig. 4 [50]. As can be seen, the size of the detector allows for the particular "pancake" shape of the acoustic emission pattern to be included in the classification of neutrino events. Background events emit spherical sound waves, while the neutrino signal is emitted in a plane. First studies indicate that for an ambient and transient background as measured at the ANTARES site, the background of neutrino-like events based on signal shape and clustering alone, as discussed in Sec. 4, can be reduced significantly when taking the emission pattern into account [50].

As a possible extension of KM3NeT beyond its final implementation with optical modules, the use of optical fibre-based hydrophones is under investigation [51]. To survey large volumes of water for acoustic signals from neutrino interactions, optical fibre-based hydrophones could potentially have several advantages over conventional hydrophones based on piezo ceramics. Optical fibres form a natural way to create a distributed sensing system in which several sensors are attached to a single fibre. The detection system in this case will consist of several sensors, an erbium doped fibre laser and an interferometric interrogator. Further advantages of this technology are low power consumption and the absence of electromagnetic interference with other readout electronics. Maybe even more important, fibre optics technology provides a cost-effective and straightforward way for the installation of a large number of hydrophones. This allows to establish a large scale experimental setup that is required for the expected low event rate of neutrino interactions at ultra-high energies. Investigations of adapting this technique to neutrino detection in combination with an under-water Cherenkov telescope are planned in the context of the KM3NeT experiment.

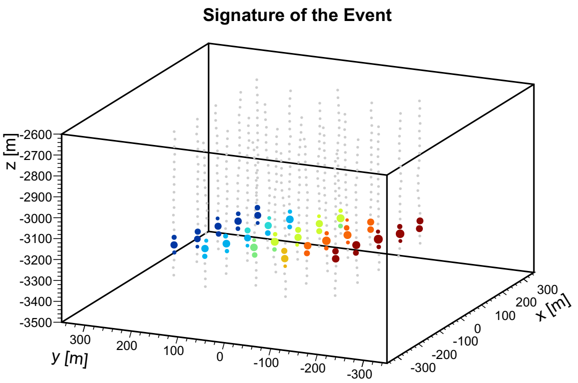

Figure 4: The signature of a neutrino event, simulated in a KM3NeT-like acoustic detector with 25 lines spaced 90 m apart. Each dot represents an optical module with an integrated acoustic sensor, while the color indicates the arrival time of the acoustic signal (red: early, blue: late, grey: not triggered). The size of the dot represents the signal amplitude. The neutrino interacted at a distance of 1.8 km from the detector center with an energy of 10^{21} eV.

6. Conclusions and Outlook

Acoustic detection is a promising approach for a future large volume detector of ultra-high energy neutrinos. To investigate the feasibility and potential of such a detector, several experiments have been performed or are underway. These experiments use either existing military acoustic arrays or are additions to Cherenkov neutrino telescopes. Their sizes are far too small to yield competitive limits on the flux of ultra-high energy neutrinos but they allow for the investigation of experimental techniques for a future acoustic neutrino detector and for the investigation of background conditions, which are the essential factor that determines the feasibility of such a device.

An acoustic extension is planned for the Gigaton Volume Detector (GVD) in Lake Baikal whereas the acoustic positioning system of the KM3NeT detector can be used parasitically for studies of acoustic neutrino detection. Studies with the existing acoustic neutrino detection test setup at Lake Baikal indicate that for a much larger setup neutrino detection with an energy threshold as low as 10^{19} eV might be possible.

For the acoustic test setup AMADEUS integrated into the ANTARES neutrino telescope in the Mediterranean Sea, the transient background is very diverse and stems mainly from sea mammals and shipping traffic. Methods for its suppression have been developed. As investigations based on the acoustic background measured with the AMADEUS setup indicate, the increased size of KM3NeT and the subsequent ability to detect the characteristic disk-like shape of the acoustic neutrino signal will reduce the expected background from transient sources dramatically.

The use of positioning hydrophones in KM3NeT would be an intermediate step towards an even bigger acoustic detector for ultra-high energy neutrinos. Such an acoustic detector could be a fibre-based hydrophone array, implemented as extension to KM3NeT.

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