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Development of acoustic devices for ultra-high energy neutrino detectors

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Acoustic neutrino detection is a promising approach to instrument the large detector volumes needed for the detection of the small neutrino fluxes expected at ultra-high energies ($E \gtrsim 1\,\mathrm{EeV}$). We report on several studies investigating the feasibility of such an acoustic detector. High-precision lab measurements using laser and proton beams aiming at the verification of the thermo-acoustic model have been performed. Different types of acoustic sensors have been developed and characterised. An autonomous acoustic system, attached to the ANTARES prototype string "Line0", has been deployed and operated successfully at 2400 m depth, allowing for in-situ studies of the acoustic background in the Mediterranean Sea.

1. Introduction

Neutrino fluxes at ultra-high energies (e.g. GZK neutrinos) are predicted to be very small. Thus large target masses are required to measure at least a few events during the lifetime of a typical experiment. The photosensor distance in water Čerenkov neutrino telescopes is limited by the attenuation length of the Čerenkov light in water or ice (50 – 70 m), constraining the affordable size of such detectors.

Another approach to neutrino detection, allowing for detectors instrumented more sparsely, is acoustic detection which was first described in [1]. The particle cascade produced by the neutrino interaction heats up the medium locally and leads to fast expansion and a bipolar pressure pulse with a typical frequency of 20 kHz, which propagates perpendicular to the cascade axis. This unique disc-shaped event signature allows for good direction reconstruction and background suppression. The sensor density in an acoustic detector is determined by the sonic attenuation length in water, which is about ten times larger than the optical attenuation length.

It is planned to deploy several acoustic sensors as part of the ANTARES neutrino telescope [2] to study the technical feasibility and environmental and background conditions of an acoustic neutrino detector. ANTARES is being installed in the Mediterranean Sea, 40 km off the coast of Toulon.

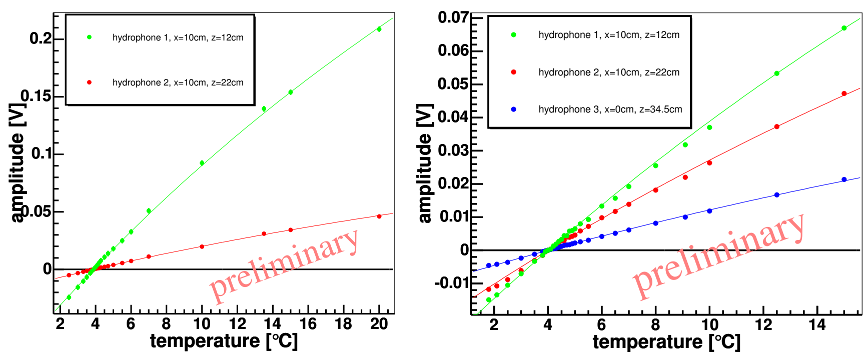
2. Tests of the thermo-acoustic model

The thermo-acoustic model describes the hydrodynamic sound generation of a particle cascade in water. The resulting pressure field is determined by the spatial and temporal distribution of the deposited energy, by the sound velocity, and by the heat capacity and the expansion coefficient, the latter two depending on temperature. Thus it is possible to test the model in the laboratory by using other means of energy deposition. This has been done with accelerator proton beams in the past [3, 4, 5].

We have performed experiments using a pulsed 1064 nm Nd:YAG laser, and the 177 MeV proton beam of the Gustaf Werner Cyclotron at the Theodor Svedberg Laboratory in Uppsala, Sweden. The beams were dumped into a $150 \times 60 \times 60\,\mathrm{cm}^3$ water tank, where the acoustic field could be measured with several position-adjustable hydrophones, both commercial and custom-designed. The temperature of the water could be varied between 1 – $50°\mathrm{C}$ with a precision of $0.1°\mathrm{C}$ by cooling and subsequent controlled, homogeneous reheating of the whole water volume.

The spill energy of the proton beam was varied from 10 to $400\,\mathrm{PeV}$. The beam diameter was $\approx 1\,\mathrm{cm}$ and the spill time $30\,\mu$s. The laser pulse energy can be adjusted between 0.1 and $10\,\mathrm{EeV}$ at a beam diameter of a few millimetres. The pulse length is fixed at 10 ns.

The measured bipolar signals are in excellent agreement with simulations made under the assumption of a thermo-acoustic signal generation mechanism. Figure 1 shows the temperature dependence of the peak-to-peak amplitude. As expected from the thermo-acoustic model, the laser beam signal shown in figure 1(a) changes its polarity around $4°\mathrm{C}$. The model expectation for the signal amplitude, which is proportional to the volume expansion coefficient (α vanishes at $4°\mathrm{C}$), is fitted to the experimental data, using an overall scaling factor, and a constant temperature shift as free parameters. This fit yields a zero-crossing of the amplitude at $(3.90 \pm 0.02)°\mathrm{C}$ which is compatible with the expectation of $(4.0 \pm 0.1)°\mathrm{C}$, where the error is dominated by the systematic uncertainty in the temperature setting. Analysing the proton data in the same way yields a shape slightly deviating from the model expectation, and a zero-crossing significantly different from $4°\mathrm{C}$. In view of the results from the laser beam measurements, we subtract the residual signal at $4.0°\mathrm{C}$, which has an amplitude of approx. $1\,\mathrm{mV}$, from all signals, assuming a non-temperature dependent effect on top of the thermo-acoustic signal. The resulting amplitudes shown in figure 1(b) are then in good agreement with the model prediction. Also signal dependencies on beam energy, beam width and sensor distance from the beam were investigated, and show very good agreement with the simulation and expectation from the thermo-acoustic model. Thus the thermo-acoustic model could be verified to high accuracy.



(a) Laser. (b) Proton beam.

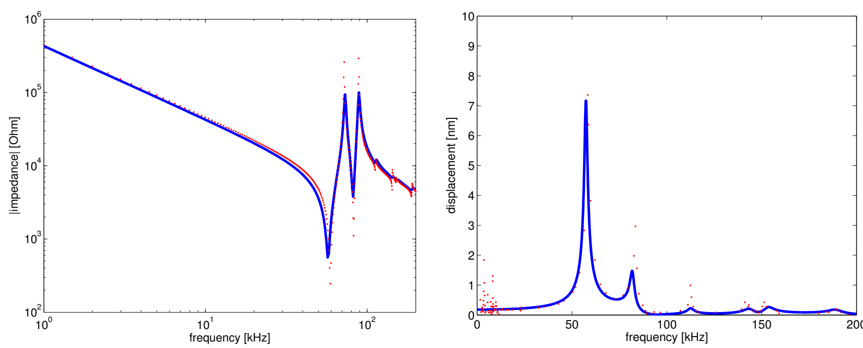
Figure 1. Dependence of the peak-to-peak amplitude of the bipolar signals on temperature for (a) the laser and (b) the proton beam. Inverted signals below $4°\mathrm{C}$ have a negative amplitude. The size of the error bars is within the size of the data points. Hydrophones at different positions relative to the beam are shown (x axis perpendicular to beam direction; z axis in beam direction).

3. Development and characterisation of acoustic sensors

It is essential for acoustic neutrino detection to understand the sensitivity and frequency response of the sensors used. We have built two different types of acoustic sensors: piezo ceramics elements, that are coated with polyurethane, or mounted into pressure tight vessels. Their electronic and acoustic properties have been investigated. The second option is particularly interesting when using glass spheres or titanium vessels that are housing the ANTARES components, since their water tightness is guaranteed, and they are easy to integrate into the existing ANTARES detector setup.

Using finite element methods, the frequency-dependent impedance of a piezo ceramic element can be calculated from the known quantities permittivity, elasticity modulus, and piezoelectric modulus. We measure the impedance by applying white noise to the piezo ceramics and analysing the frequency spectrum of the voltage measured at a capacitor in serial connexion. Figure 2(a) shows that with this method, the electrical properties of a piezo can be predicted very well, allowing for the design of piezo element geometries that are well matched to the needs of acoustic particle detection.

Further, interferometric measurements of the dependence of the displacement of the piezo ceramics surface on the applied voltage have been carried out, that allow for direct calibration of the piezo ceramics sensitivity to external pressure signals. A laser beam is coupled into an optical fibre and exits through a fibre end, which is prepared carefully to behave like a mirror. The beam is reflected multiple times between this end and a thin, gold coated glass plate a few micrometres away, that is mounted onto the piezo ceramics surface. Both surfaces act as a Fabry-Perot interferometer. The light, that, at each reflection on the fibre end, is coupled back into the fibre, is measured behind a beam splitter, allowing for the determination of distance variations between the fibre end and the piezo ceramics surface. In figure 2(b) excellent agreement between the measurement and finite element calculations based on material properties can be seen.



(a) Impedance. (b) Displacement amplitude.

Figure 2. Measured frequency dependence (a) of the impedance of a piezo ceramic element (red dots) compared to predictions from the mechano-electrical model (blue line), and (b) of the displacement amplitude of the piezo ceramics surface. In both plots the resonances from the piezo element are well visible.

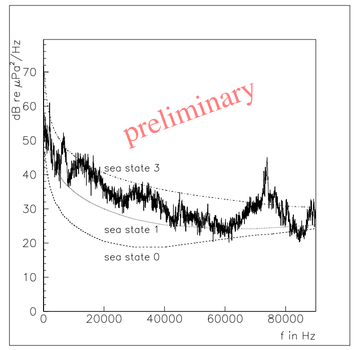
The properties of "naked" piezo ceramics can be well described with the methods presented, thus piezo ceramics with high sensitivity for applications like acoustic particle detections can be designed. The properties of coated piezo ceramics or piezo ceramics coupled to pressure tight vessels are under study.

4. AMADEUS – Autonomous Module for Acoustic DEtection Under the Sea

In spring 2005 an autonomous acoustic data acquisition system (AMADEUS) was deployed and operated successfully at a depth of 2400 m together with the ANTARES prototype test string "Line0" in order to study the acoustic background at the ANTARES site. It consisted of five piezo ceramic sensors glued to the inside of a pressure tight titanium cylinder normally used for the ANTARES electronics (cf. figure 3(a)). The sensors where read out using a 16-bit ADC board with an integral sampling rate of 500 kHz. In order to suppress noise from the hard disk, data was stored on a flash card, and written to disk when no data was recorded. In different operation modes it was possible to read out a single sensor with a high data-rate, or multiple sensors in coincidence. A total of 12 hours of acoustic data were taken.

The analysis of a first part of the data, which was recorded during a first descent of the line, a short period on the sea-floor, and the recovery operation, shows the usability of the concept to couple piezo ceramic sensors to the inside of a pressure tight support structure in order to detect acoustic signals in the deep sea. Figure 3(b) shows a preliminary noise spectrum measured at the bottom of the Mediterranean sea, which is in good agreement with expectations.

(a) View into the AMADEUS cylinder from the top.



(b) Noise spectrum.

Figure 3. In (a) the four yellow sensors glued to the walls of the cylinder can be seen; the fifth sensor is mounted onto the top cover. The noise power density in (b) fits nicely between the predictions for sea states one and three (taken from [6]).

5. Conclusions

We have demonstrated, that the thermo-acoustic model describing the sound generation of high-energy particle cascades is understood up to high precision, which is imperative in order to build a neutrino telescope based on acoustic detection. As a first step towards such a detector, different types of acoustic sensors were investigated and their properties were predicted from basic principles, allowing for the development of tailor-made sensors. Acoustic background data was collected in-situ in the Mediterranean sea at a depth of 2400 m.

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