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Acoustic detection of UHE neutrinos: Status and perspective

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Summary. — In recent years the astro-particle community is involved in the realization of experimental apparatuses for the detection of high-energy neutrinos originated in cosmic sources or produced in the interaction of cosmic rays with the cosmic microwave background. For neutrino energies in the TeV-PeV range, the underwater optical Cherenkov technique is considered optimal. For higher energies, three experimental techniques are under study: the detection of radio pulses produced by showers following a neutrino interaction, the detection of air showers initiated by neutrinos interacting with rocks or deep Earth's atmosphere and the detection of acoustic waves produced by deposition of energy in the interaction of neutrinos in acoustically transparent mediums. The acoustic detection technique is based on the thermo-acoustic effect, first proposed by Askaryan in 1957. The deposit of the cascade energy in a small volume of suitable medium such as ice, water or salt, 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. The quasi-instantaneous expansion of the medium results in a coherent production of a collimated mechanical wave propagating, in a homogeneous medium, perpendicularly to the shower axis. Different groups are conducting studies to characterize acoustic properties of different mediums and developing the technologies required for future large-scale acoustic arrays. Test experiments were carried out using military arrays of hydrophones or available scientific infrastructures and first searches for neutrino signals were performed. Though the studies on this technique are still in an early stage, its potential use to build very large neutrino detectors is appealing, thanks to the optimal properties of mediums such as water, ice or salt as sound propagator. The status of simulation work, medium studies, sensor developments and first results from test experimental setups will be discussed.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.

1. – The thermo-acoustic mechanism

The acoustic detection technique of neutrino-induced cascades, in water or ice, is based on the thermo-acoustic effect, first suggested by Askarian in 1957 [1]. The cascade energy is deposited in a narrow region of the medium, induces a local heating and results in a rapid expansion of the water (or ice). The medium expansion results in the emission of an impulse of pressure described by the following wave equation:

$$\frac{1}{C_s^2}\frac{\partial^2 p(\vec{r},t)}{\partial t^2} - \nabla^2 p(\vec{r},t) = \frac{\beta}{C_p}\frac{\partial^2 q(\vec{r},t)}{\partial t^2}\,. \tag{1}$$

In this equation p is a small deviation from the hydrostatic pressure (in the position r and at the time t) and C_s is the speed of sound in the medium. The source term in this equation is the so-called thermo-acoustic term in which q is the energy density, β is the expansion coefficient and C_p is the specific heat capacity at constant pressure. It is convenient to group the environmental parameters in an adimensional one, the Gruneissen parameter γ

$$\gamma = \frac{\beta C_s^2}{C_p}\,. \tag{2}$$

This parameter expresses the conversion efficiency of the thermal energy into sound. Equation (1) can be simplified, since the energy deposition is almost instantaneous and solved using the Kirchhoff integral:

$$p(\vec{r},t) = \frac{\gamma}{4\pi}\frac{\partial}{\partial R}\int_S \frac{q(\vec{r}\,')}{R}\mathrm{d}\sigma. \tag{3}$$

The thermo-acoustic model allows to describe how the energy deposited in a medium, by a high-energy cascade, generates a pressure wave. It is possible to test this model in the laboratory using other ways to deposit energy in the medium. Two different kinds of approaches have been carried out in past years: experiments using high intensity and low energy particles beams [2] (beam-dump) and experiments using a laser beam [3]. In beam-dump experiments the energy deposition in water is obtained using a proton beam; the protons energy is transferred to the medium by ionization and proton-nucleus scattering. The energy of each proton bunch is mostly released at the end of its path, the so-called Braggs peak, since the energy loss per unit of length increases as the energy decreases. This generates an energy deposition that is roughly pointlike. Laser beam experiments are conceptually identical to the beam-dump ones but use a different technique to release energy in the medium; as the laser propagates in water its intensity decreases exponentially releasing energy to the medium by exciting the rotational and vibrational modes of the water molecules. All the experiments reported in the literature have validated the thermo-acoustic model in principle even if the results have large systematic and statistical errors.

2. – Neutrino interactions and high-energy showers development

The neutrino interaction with the nucleons of the medium could be of two types: a) charged current interaction (CC) $\nu_\ell(\bar{\nu_\ell}) + N \rightarrow \ell^\pm + X$, where the subscript ℓ indicates the lepton flavour (e, μ, τ). In this type of interactions the neutrino converts into the corresponding lepton and the kinetic energy transferred to the nucleon generates a hadronic shower. b) Neutral current interaction (NC) $\nu_\ell(\bar{\nu_\ell}) + N \rightarrow \nu_\ell(\bar{\nu_\ell}) + X$. In this

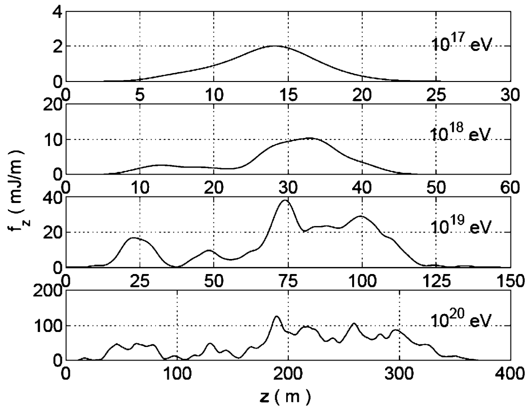

Fig. 1. – Energy density profile of an electromagnetic shower at different energy. As the LPM effect starts to play a significant role the shower length increases; this prevents the energy density to increase linearly with the neutrino energy.

kind of interactions the only visible part of the final state is the hadronic shower. In a wide range of energy the ratio of the CC cross-section over the total one is [4]

$$\frac{\sigma_{CC}}{\sigma_{CC}+\sigma_{NC}} \approx 0.7; \tag{4}$$

this means that in about 70% of the neutrino interactions with nucleons there is the production of a charged lepton. It is especially important which part of the neutrino energy is transferred to the hadronic cascade in NC and CC interactions. The kinematical variable which is relevant in this case is the Bjorken variable y. As reported by Gandhi the mean inelasticity $\langle y\rangle$, for $E_\nu > 10^{15}$ eV, is weakly dependent on energy and its value is about 20%. From these considerations it might seem that the golden events are the electromagnetic showers produced during the CC interactions, which are the most abundant and retains about 80% of the incident neutrino energy. Unfortunately this is not the case at very high energy. It was first noticed [5,6] by Landau, Pomeranchuk and Migdal (LPM) that above a threshold of about 10^{17} eV, the cross-sections for bremsstrahlung and pair production decrease as E. As a consequence the shower becomes longer and subshowers will develop along the main shower as the particle energy drops below the LMP threshold; the longitudinal profile of one cascade above the LPM threshold is shown in fig. 1.

One of the most important features of the acoustic signal produced by a shower is its angular distribution. As pointed out in the previous section the energy deposition could be considered as instantaneous and so the sound generation (pressure wave from water expansion) along the shower. The simultaneous sound production along the shower results in a very collimated, coherent emission in the plane perpendicular to the shower axis. Many groups have performend detailed simulations of the neutrino interaction and shower development [7-10]; as an example, in fig. 2 and fig. 3 the neutrino acoustic pulse shape and its radiation pattern, as results from Learned simulations, are reported.

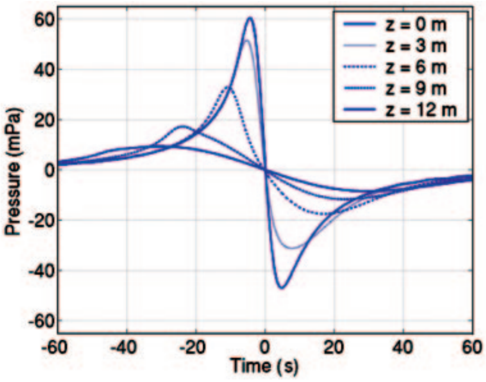

Fig. 2. – Pressure pulse for a neutrino of 10^{20} eV measured at 1 km distance. Z is the vertical displacement from the shower center.

3. – Pilot experiments

Many collaborations [10-15], all over the world, are working on the acoustic neutrino detection, giving important contributions on varius topics; in the following I briefly summarize some of the most relevant.

3˙1. *SAUND*. – The SAUND experiment uses seven hydrophones of a military array located at the Bahamas 1100 m depth; despite of the low number of hydrophones and of the fact that their position and their electronic readout (100 ksps with resolution of 12 bit) has not been optimized for the neutrino detection the SAUND Collaboration was able to set the first upper limit for the diffuse neutrino flux, in the energy range $E > 10^{22}$ eV using an acoustic detection technique. Their result, obtained with 15 days of data-taking, is reported in fig. 4. SAUND II will use 56 hydrophones from the same array, over a surface of about 1000 km^2 and is supposed to take data for about one year.

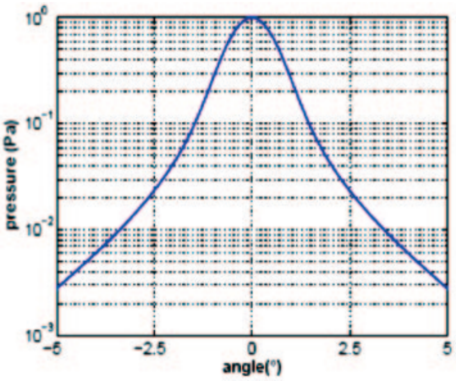

Fig. 3. – Far-field radiation pattern as a function of the azimuthal emission angle. The intensity of the sound pulse decreases by about 20 dB in 3 degrees.

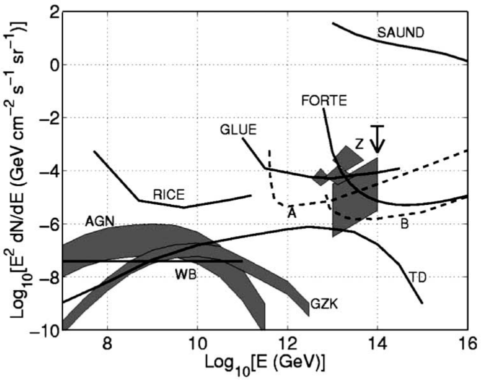

Fig. 4. – Summary of the upper limit to a diffuse neutrino flux set by different experiments (solid line labeled SAUND, GLUE, RICE). In the figure the neutrino flux predicted by different theoretical models are reported: Z for different models of Z burst, AGN for active galactic nuclei, TD for neutrino generated by topological defects and WGB for the Waxmann-Bahcall limit. The dashed lines labeled as A and B are the sensitivity of two different acoustic arrays discussed in [10].

3·2. *ANTARES-AMADEUS*. – The AMADEUS project is fully integrated into the ANTARES [12] Cherenkov neutrino telescope. Its main goal is to evaluate the feasibility of a future acoustic neutrino telescope in the deep sea operating in the ultra-high energy regime. AMADEUS is at the moment the biggest underwater acoustic array that is continuosly taking data. It is composed of 6 arrays each made of 6 hydrophones sampled at 200 kHz with a resolution of 16 bit. The spacing inside each array is of the order of 1 m, while the spacing between the arrays varies from ∼ 15 m to ∼ 300 m. One array is equipped with self-made hydros with typical sensitivity of about −145 dB re 1 V/μPa. The AMADEUS project is performing a long-term background investigation and its correlation with ambient [16] and is a unique opportunity to test detection and event reconstruction algorithms and to study hybrid detection methods (optic and acoustic).

3·3. *NEMO-Oνde*. – A major source of information about the background noise in deep water is the Oνde [11] experiment, realized in the framework of the NEMO [17] Collaboration. Oνde is an acoustic station installed at the NEMO test site, 20 km off the Sicily coast in front of Catania at depth of 2000 m and is composed by an array of four hydrophones sampled at 96 kHz with a resolution of 24 bit. The station has performed sound background monitoring from January 2005 up to November 2006. One of the most remarkable, and nearly unique, results obtained by Oνde is the noise power spectral density measured in deep water (2000 m) and reported in fig. 5.

3·4. *NEMO Phase II*. – The NEMO Collaboration aims the construction of a km^3 Cherenkov neutrino telescope in the Mediteranean sea. The deployment of a tower composed by 8 floors is foreseen during the next year. The tower will be equipped with a new acoustic positioning system. A new hydrophone, the SMID TR-401, and a preamplifier, SMID AM-401, have been developed by SMID specifically for this system. The hydrophones calibration curves were measured at 1 bar pressure at the NATO Undersea Research Centre of La Spezia (Italy), showing that the average sensitivity is about -172 ± 3 dB re 1 V/μPa in the frequency range 1 kHz–70 kHz. The relative change of

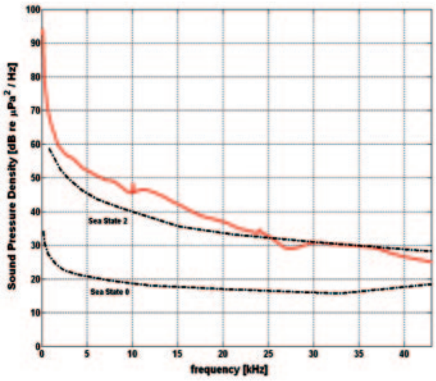

Fig. 5. – Underwater noise measured by Oνde at 2000 m depth in the NEMO test site.

hydrophones sensitivity as a function of pressure was also measured using an innovative calibration technique. The change of sensitivity, as a function of pressure, is extremely low and turns out to be less than 1 dB. The hydrophone data, sampled at 192 ksps with a resolution of 24 bit, will be continuously sent to the on-shore laboratory; the array is fully integrated into the NEMO acquisition system, this means that the whole hydrophone array is synchronised and phased to GPS clock.

4. – Conclusions

Though the studies on this technique are still in an early stage, its potential use to build very large neutrino detectors is appealing, thanks to the optimal properties of mediums such as water, ice or salt as sound propagators. Several reliable codes are available to simulate neutrino interactions and ultra high energy showers in different medium. Water properties are well known, even if a deep sea site for a large installation would require further studies. The technology is mature for high-precision measurement but further study is necessary to manage large instrumented volume. In my opinion is of fundamental importance to look for hybrid events (acoustic/radio/optic) to provide final validation of the technique and the possibility to perform an intercalibration study to reduce the systematics.

REFERENCES

[1] Askaryan G. A., *Sov. J. At. Energy*, **3** (1957) 921.
[2] Sulak L. *et al.*, *Nucl. Intrum. Methods Phys. Res.*, **161** (1979) 203.
[3] Schwemmer S., Diploma thesis, FAU-PI1-DIPL-05002 (2005).
[4] Gandhi R. *et al.*, *Phys. Rev. D*, **58** (1998) 093009.
[5] Askaryan G. A., *Dokl. Akad. Nauk USSR*, **92** (1953) 535.
[6] Migdal A. B., *Phy. Rev.*, **103** (1956) 6.
[7] Niess V., Doctoral thesis, `http://marwww.in2p3.fr/~niess/these.pdf` (2006).
[8] Perkin J., Doctoral thesis, `http://arxiv.org/PS_cache/arxiv/pdf/0801/0801.0991v1.pdf` (2007).
[9] Learned J. G. *et al.*, *Astropart. Phys.*, **17** (2002) 279.
[10] Lehtinen N. G. *et al.*, *Astrophys. J.*, **621** (2005) 301.
[11] Riccobene G. *et al.*, arXiv:0804.2913v1.

[12] The ANTARES site `http://antares.in2p3.fr/`.
[13] The BAIKAL site `http://www.ifh.de/baikal/baikalhome.html`.
[14] The ICECUBE site `http://icecube.wisc.edu/`.
[15] The ACORNE site `http://www.hep.shef.ac.uk/research/acorne/`.
[16] SIMEONE F. on behalf of the ANTARES Collaboration, arXiv:0908.0862.
[17] The NEMO site `http://nemoweb.lns.infn.it/`.