Astroparticle Physics 65 (2015) 69–79

Contents lists available at ScienceDirect

Astroparticle Physics

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

Thermo-acoustic sound generation in the interaction of pulsed proton and laser beams with a water target

R. Lahmann [a,*], G. Anton [a], K. Graf [a], J. Hößl [a], A. Kappes [a], U. Katz [a], K. Mecke [b], S. Schwemmer [c,1]

[a] Erlangen Centre for Astroparticle Physics (ECAP), Friedrich-Alexander-Universität Erlangen-Nürnberg, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
[b] Institut für Theoretische Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 7, 91058 Erlangen, Germany
[c] Landessternwarte, Königstuhl 12, 69117 Heidelberg, Germany

ARTICLE INFO

Article history:
Received 6 August 2014
Received in revised form 7 November 2014
Accepted 8 December 2014
Available online 17 December 2014

Keywords:
Cosmic neutrinos
Acoustic neutrino detection
Thermo-acoustic model
Ultra-high energy cosmic rays
Beam interaction

ABSTRACT

The generation of hydrodynamic radiation in interactions of pulsed proton and laser beams with matter is explored. The beams were directed into a water target and the resulting acoustic signals were recorded with pressure sensitive sensors. Measurements were performed with varying pulse energies, sensor positions, beam diameters and temperatures. The obtained data are matched by simulation results based on the thermo-acoustic model with uncertainties at a level of 10%. The results imply that the primary mechanism for sound generation by the energy deposition of particles propagating in water is the local heating of the medium. The heating results in a fast expansion or contraction and a pressure pulse of bipolar shape is emitted into the surrounding medium. An interesting, widely discussed application of this effect could be the detection of ultra-high energetic cosmic neutrinos in future large-scale acoustic neutrino detectors. For this application a validation of the sound generation mechanism to high accuracy, as achieved with the experiments discussed in this article, is of high importance.

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 [2–8].

The interest in characterising the properties of the acoustic radiation was, among other reasons, lead by the idea that the effect can be utilised to detect ultra-high energy ($E \gtrsim 10^{18}$ eV) cosmic, i.e. astrophysical neutrinos, in dense media like water, ice and salt. In the 1970s this idea was discussed within the DUMAND optical neutrino detector project [9] and has been studied in connection with Cherenkov neutrino detector projects since. The detection of such 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 [10–12]. Due to the low expected fluxes, detector sizes exceeding 100 km^3 are needed [13]. However, the properties of the acoustic method allow for sparsely instrumented arrays with $\sim$100 sensors/km^3.

To study the feasibility of a detection method based on acoustic signals it is necessary to understand the properties of the sound generation by comparing measurements and simulations based on theoretical models. According to the so-called thermo-acoustic model [2], the energy deposition of particles traversing liquids leads to a local heating of the medium which can be regarded as instantaneous with respect to the hydrodynamic time scales. Due to the temperature change the medium expands or contracts according to its bulk volume expansion coefficient α. The accelerated motion of the heated medium generates an ultrasonic pulse whose temporal signature is bipolar and which propagates in the volume. Coherent superposition of the elementary sound waves, produced over the cylindrical volume of the energy deposition, leads to a propagation within a flat disk-like volume in the direction perpendicular to the axis of the particle shower.

In this study, the hydrodynamic signal generation by two types of beams, interacting with a water target, was investigated: pulsed protons and a pulsed laser, mimicking the formation of a hadronic cascade from a neutrino interaction under laboratory conditions. With respect to the aforementioned experimental studies of the thermo-acoustic model, the work presented here can make use of previously unavailable advanced tools such as GEANT4 [14] for the

* Corresponding author.
E-mail address: robert.lahmann@physik.uni-erlangen.de (R. Lahmann).
[1] formerly at ECAP.

http://dx.doi.org/10.1016/j.astropartphys.2014.12.003
0927-6505/

simulation of proton-induced hadronic showers in water. Good agreement was found in the comparison of the measured signal properties with the simulation results, providing confidence to apply similar simulation methods in the context of acoustic detection of ultra-high energy neutrinos. A puzzling feature observed in previous studies—a non-vanishing signal amplitude at a temperature of 4 °C, where for water at its highest density no thermo-acoustic signal should be present—was investigated in detail. Such a residual signal was also observed for the proton beam experiment described in this article, but not for the laser beam, indicating that the formation of this signal is related to the charge or the mass of the protons.

2. Derivation of the model

In the following, the thermo-acoustic model [2,3] is derived from basic assumptions, using a hydrodynamic approach. Basis is the momentum conservation, i.e. the Euler Equation

$$\frac{\partial(\rho v_i)}{\partial t} = -\sum_{j=1}^{3}\frac{\partial \Pi_{ij}}{\partial x_j}, \tag{1}$$

for mass density ρ, velocity vector field of the medium (v_1, v_2, v_3) and momentum-density tensor

$$\Pi_{ij} = p\delta_{ij} + \rho v_i v_j \tag{2}$$

including the pressure p [15]. Eq. (1) can be derived from momentum conservation. In the derivation, energy dissipation resulting from processes such as internal friction or heat transfer are neglected. Motions described by the Euler Equation hence are adiabatic. Taking the three partial derivatives of Eq. (1) with respect to x_i and using for the density the continuity equation

$$\frac{\partial \rho}{\partial t} + \sum_{i=1}^{3}\frac{\partial}{\partial x_i}(\rho v_i) = 0, \tag{3}$$

a non-linear wave equation can be derived:

$$\frac{\partial^2 \rho}{\partial t^2} = \sum_{i,j=1}^{3}\frac{\partial^2 \Pi_{ij}}{\partial x_i \partial x_j}. \tag{4}$$

To solve this equation, the problem is approached in two separated spatial regions: Firstly, a region B (*'beam'*), where the energy is deposited in the beam interactions with the fluid and thus the wave excited in a non-equilibrium process; and secondly, a hydrodynamic (*'acoustic'*) region A, where the acoustic wave propagates through the medium and where linear hydrodynamics in local equilibrium can be assumed. This splitting can be reflected by the momentum density tensor, rewriting it as

$$\Pi_{ij}(\vec{r}) = \begin{cases} \Pi^A_{ij}(\vec{r}) & \text{for } \vec{r} \in A \\ \Pi^B_{ij}(\vec{r}) & \text{for } \vec{r} \in B \end{cases}. \tag{5}$$

In local equilibrium the changes in mass density are given by

$$d\rho = \left.\frac{\partial \rho}{\partial p}\right|_{S,N} dp + \left.\frac{\partial \rho}{\partial S}\right|_{p,N} dS = \frac{1}{v_s^2}dp - \frac{\alpha}{c_p}\frac{\delta Q}{V} \tag{6}$$

with the bulk volume expansion coefficient $\alpha = -\frac{1}{\rho}\frac{\partial \rho}{\partial T}|_{p,N}$, the energy deposition $\delta Q = TdS$, the adiabatic speed of sound v_s in the medium and the specific heat $c_p = \frac{T}{N}\frac{\partial S}{\partial T}|_{p,N}$.

In the acoustic regime, where $\delta Q = 0$, the momentum density tensor can be expressed as $\Pi^A_{ij} = p\delta_{ij} = v_s^2\rho\delta_{ij}$ (using Eqs. (2)), where we assume an adiabatic density change with pressure. The non-linear kinetic term $\rho v_i v_j$ entering Π^A_{ij} according to Eq. (2) can be neglected for small deviations $\rho' = \rho - \rho_0$ from the static density ρ_0 and small pressure differences $p' = p - p_0$ from the static pressure p_0 [15].

In the region B, where non-equilibrium deposition occur, one may make the *ansatz*

$$\Pi^B_{ij} = p\delta_{ij} + \beta u_i u_j \tag{7}$$

with the direction u_i of the beam which breaks the isotropy of the energy–momentum tensor and describes with the parameter β in an effective way the momentum transfer on the fluid.

Although in non-equilibrium we apply Eq. (6) with the energy deposition density $\epsilon \equiv Q/V$ of the beam. Then, with the additional energy–momentum tensor due to the beam

$$\delta\Pi^B_{ij} := v_s^2\frac{\alpha}{c_p}\epsilon\delta_{ij} + \beta u_i u_j$$

the wave Eq. (4) reads

$$\vec{\nabla}^2 p' - \frac{1}{v_s^2}\frac{\partial^2 p'}{\partial t^2} = -\sum_{i,j=1}^{3}\frac{\partial^2 \delta\Pi^B_{ij}}{\partial x_i \partial x_j} \tag{8}$$

The general solution for the wave equation can be written using a Green function approach as

$$p'(\vec{r},t) = \frac{1}{4\pi}\sum_{i,j=1}^{3}\int_B dV'\frac{1}{|\vec{r}-\vec{r}'|}\frac{\partial^2\delta\Pi^B_{ik}(\vec{r}',t')}{\partial x'_i \partial x'_k} = \frac{1}{4\pi}\int_B dV' \left[\frac{n_i n_k}{|\vec{r}-\vec{r}'|}\frac{\partial^2\delta\Pi^B_{ik}(\vec{r}',t')}{v_s^2\partial t'^2} + \frac{3n_i n_k - \delta_{ik}}{|\vec{r}-\vec{r}'|^2}\left(\frac{\partial\delta\Pi^B_{ik}(\vec{r}',t')}{v_s\partial t'} + \frac{\delta\Pi^B_{ik}}{|\vec{r}-\vec{r}'|}\right)\right] \tag{9}$$

with the components of the unit vector $n_i = (x_i - x'_i)/|\vec{r}-\vec{r}'|$ and the retarded time $t' = t - |\vec{r}-\vec{r}'|/v_s$. For the last conversion, partial integration and the total derivative $\frac{d}{dx_i} = \frac{\partial}{\partial x_i} + \frac{1}{v_s}\frac{\partial}{\partial t}$ have been used repeatedly. Note that $\delta\Pi^B_{ij} = 0$ for $\vec{r} \in A$, so that the integration is carried out over the volume of the energy deposition region B.

Assuming an energy deposition without momentum transfer to the medium, the kinetic term in the *ansatz* (7) can be neglected ($\beta = 0$) yielding

$$p'(\vec{r},t) = \frac{1}{4\pi}\frac{\alpha}{c_p}\int_V \frac{dV'}{|\vec{r}-\vec{r}'|}\frac{\partial^2}{\partial t^2}\epsilon(\vec{r}',t') \tag{10}$$

for a thermo-acoustic wave generated solely by heating of the medium. The signal amplitude p' can be shown to be proportional to the dimensionless quantity $v_s^2\alpha/c_p$ when solving Eq. (10) for the case of an instantaneous energy deposition.

Eq. (10) is equivalent to the results obtained from the approaches presented in [2,3]. The derivation pursued above, however, uses a different approach starting with the Euler equation and an anisotropic energy–momentum tensor, yielding a more general expression in Eq. (9). Only if assuming an isotropic energy deposition one arrives at the expression for the pressure deviation p' given in Eq. (10).

Note that the validation of the last assumption $\beta = 0$ being a good approximation would require a detailed knowledge of the momentum transfer from the beam to the medium. Taking it into account would result in an additional dipol term $\sim \ddot{\beta}(\vec{u}\cdot\vec{n})^2$ in Eq. (10) which may become the dominant contribution to wave generation if $\alpha \approx 0$ close to 4.0 °C. However, for $\beta = 0$ the pressure field resulting from a beam interaction in a medium is determined by the spatial and temporal distribution of the energy deposition density ϵ alone. The amplitude of the resulting acoustic wave is governed by the thermodynamic properties v_s, c_p and α, the latter three depending primarily on the temperature of the medium. A controlled variation of these parameters in the conducted laboratory experiments and a study of the resulting pressure signals therefore allows for a precise test of the thermo-acoustic model.

Simulations based on the thermo-acoustic model, as performed to interpret the results of the experiments described in the next section, will be discussed in Section 5. Note that the energy deposition density ϵ and its temporal evolution for the proton and laser