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Studies of radio emission from neutrino induced showers generated in rock salt

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ABSTRACT

Radio emission from particle showers can be used as a method of neutrino detection in the high and very high energy range as a Cherenkov pulse originates from the charge excess developing in the medium. Our study presents simulations of neutrino induced showers in rock salt and the radio emission that they generate, using the HERWIG, GEANT4 and AIRES codes. We have performed a complete study of all neutrino flavours interacting on nuclei, both for charged-current and neutral-current interactions, using the knowledge and codes available today. As primary neutrino energies we have chosen three values: 10^{12} eV, 10^{15} eV and 10^{17} eV. We have injected all the particles resulting from the first interactions into shower simulation codes.

Salt is one of the dielectric media proposed for radio detection of neutrinos already in the sixties of last century, and can be found in large volumes throughout the world.

The calculation of the radio signal was performed considering the entire shower evolution, by approximating the shower with a current density. We have taken into account, in the equations, only the longitudinal profile. The aim of this study is to investigate whether different interactions can be discriminated in an experiment for detection of high energy particles based on the radio emission from the showers they initiate in a dense medium. For this we have performed and systematically analyzed simulations from several points of view.

1. Introduction

In contrast to charged particles and photons, ultrahigh energy (UHE) cosmic neutrinos are able to travel long distances from the far and early Universe and hardly experience the cooling and damping effects from the cosmic background radiation filling the Universe.

The detection of such neutrinos will require a detector volume of several tens of cubic kilometers water equivalent instrumented mass, and a solid angle of about 1 sr. There are several approaches for such large volume detectors, in particular the Cherenkov detectors like the RICE [1], AMANDA [2], ANTARES [3] and IceCube [4] set-ups. Optical techniques are widely used by these detectors, but the effective volume which can be instrumented is constrained by the attenuation lengths of optical frequencies in the detector media so that, alternatively, the observation of radio waves gains interest for huge neutrino detectors. Actually there are serious efforts in this direction by the ANITA [5] experiment and the ARA proposal [6]. An extensive review on the status and perspectives in high energy neutrino astrophysics can be found in [7].

Fifty years ago Askaryan [8,9] proposed to detect high energy particles by the electromagnetic pulses which they emit by their interaction in dense media. Due to the processes that take place during the evolution of the shower a negative charge excess appears. This material dependent charge excess generates Cerenkov radiation that can be registered. In dense dielectric and radio transparent media, such as ice, sand and salt (proposed by Askaryan in 1965 [9,10]), the length of the shower in the material can vary from a few meters at low energies to a few tens of meters at the highest energies. Thus, the electromagnetic radiation in the radio domain is added coherently for all the particles generating it. If the medium is transparent and has low attenuation lengths the signal can be observed at large distances.

It should be noted that the observation of radio emission from showers in a low density medium, air, has found a revival of interest in recent years, [11,12], after the first attempts in 1965 [13].

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The development of extensive air showers is influenced by the geomagnetic field. This feature changes the character of the dominant mechanism.

Applicability of the radio technique for detection of energetic particles, such as astrophysical or cosmogenic neutrinos, using the Askaryan effect, is an important issue. As long as the power of the radio signal scales with the square of the number of particles generating the coherent pulse, detection of emission from showers is measurable for primary energies of the incident particle which are of the order of PeV and higher. The best candidates for this type of detection are high energy cosmic neutrinos, mainly because the volumes needed are situated underground and thus benefit from shielding from secondary cosmic rays.

For the present study we have chosen rock salt as the detection medium. Rock salt is a dielectric radio transparent medium. Among the materials proposed by Askaryan it has the highest density, which leads to the increase of the neutrino interaction probability. This also shortens the length of the shower, increasing the probability that the shower develops entirely into the detector volume. On the other hand a short shower also induces a radio signal short in time, increasing the difficulty to detect it at low energies.

For detection in salt, some preliminary studies have been made, and tests have been performed for the investigation of material properties [14–18]. The proposal for a detection grid in salt, SALSA (Saltdome Shower Array) [19], has so far not been pursued due to difficulties at the location. Besides the crucial experimental investigations further theoretical studies and simulations are necessary to asses the criteria which a high energy particle detector in salt must meet and to establish a basis of simulations and predictions of results for the time when such a detector would be constructed. In the background of the present studies is the idea to use eventually a local salt mine in Romania for experimental studies of the Askaryan effect.

The present calculations of the radio emission apply the algorithm of Alvarez-Muniz et al., first described in [20], to rock salt and consider all neutrino flavours interacting with the medium by charge-current as well as by neutral-current interactions at various primary neutrino energies. Even if τ neutrinos are not expected to be produced at the astrophysical source, approximately equal fluxes for each neutrino flavour should reach the Earth as a result of neutrino oscillations over cosmological distances, and therefore we have also considered τ neutrinos.

The different particle components resulting from the first neutrino interactions with the medium induce electromagnetic and hadronic showers, which are simulated by the GEANT4 [22] and AIRES [23] codes. Using methods employed in classical electrodynamics the radiation induced by the charge excess is calculated.

In order to study the realistic case of a neutrino interacting in salt, described in Section 2, and generating a radio signal we simulate the first interaction in an external event generator, as presented in Section 3, using the Fortran based HERWIG 6.5 code [24]. The products of the first interaction are then injected into GEANT4 and AIRES simulations, according to their primary energy, and the corresponding averaged longitudinal profiles are presented in Section 4. So far, for salt, this approach has not been considered as it is assumed that at high energies only the contribution of the secondary lepton is important. A complete approach, considering the entire shower, simulated with AIRES or CORSIKA [25] codes, has been considered for air [29,30], for individual showers. In ice neutrino induced showers have been studied considering lepton induced shower [26,27]. In [28] showers induced by a NC neutrino interaction in ice were also considered.

The electric fields for the simulated showers are calculated, both in time and frequency domain, in Section 5. Section 6 presents the conclusions.

In this work we study the radio emission from neutrino induced showers in order to search for features that would make discrimination possible in a future experiment. However, we do not approach any experimental details.

2. The medium, salt

Rock salt, also named halite, is the mineral form of sodium chloride NaCl. Halite forms isometric crystals, 1 sodium (Na) atom to 1 chlorine (Cl) atom, and it is typically colourless to yellow, but it may also be light blue, dark blue or pink depending on the amount and type of the impurities present. It commonly occurs with other evaporite deposit minerals such as several of the sulfates, halides and borates. The initial salt deposit is the result of layers of dried solutes (evaporites) of ancient seas forming a layered structure. Each layer has different characteristics according to the deposited sediments. The East Carpathians Bend area, in Romania, where the Slanic salt deposit is located, has a complex structure characterized by the presence of nappes, their post-tectonic cover and salt diapirs formed in the Early Miocene age [31].

Before starting any experimental activities looking for radio emission induced in rock salt the suitability of the particular medium must be investigated. Differences in quality of the mineral, mainly impurities, induce changes in permittivity and scatter centers. Mechanical fractures may cause dispersion and changes in refraction. All of these effects influence the transmission of the radio signal from source to observer.

General properties of the salt can be found in Table 1. For comparison same properties for ice are also listed.

Salt has been tested for radio transmission in different locations [15,17] and found to be satisfactory for detection at relatively small distances, few tens of meters. Some preliminary transmission tests have also been performed on the Slanic Prahova rock salt from Romania [32].

3. First interaction of neutrinos

At high primary energies the dominant interaction mechanism of neutrinos is deep inelastic scattering on nucleons. The charged-current (CC) and neutral-current (NC) deep inelastic scatterings are mediated by the charged or neutral vector bosons, $W^{\pm}$ and Z^0. The CC interactions are:

$$\nu_l(\tilde{\nu}_l) + N \rightarrow l^-(l^+) + X. \quad (1)$$

And the NC interactions are:

$$\nu_l(\tilde{\nu}_l) + N \rightarrow \nu_l(\tilde{\nu}_l) + X, \quad (2)$$

where l denotes a lepton, N represents a nucleon, n or p and X, other secondary fragments, called hereafter the X fragments.

At the highest energies in the charged-current (CC) interaction of an electron neutrino a mixed shower is generated. A large fraction of the primary energy goes into an electron (positron), which will produce an electromagnetic shower along with the hadronic shower induced by the X fragments. The CC interaction of a ν_μ produces a hadronic shower and a muon which will penetrate deep into the material and lose small amounts of energy, as it propagates. Tau neutrinos produce tau leptons in CC interactions, which, depending on the decay length and decay modes of the tau, generate sub-showers and add to the hadronic shower, if they are close to the position of the primary neutrino interaction, or create independent sub-showers if the decay occurs far from the primary interaction vertex.

The neutral-current (NC) interaction of all three flavours results in purely hadronic showers, generated by the X fragments alone.