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RADIO EMISSION FROM NEUTRINO INDUCED SHOWERS IN SALT USING SIMULATIONS PERFORMED WITH GEANT4 AND AIRES CODES*

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Abstract. We present here calculations of radio emission from neutrino induced showers in the context of detection of high energy particles in large volumes employing the radio waves that the shower generates. The medium chosen is salt, one of the media proposed by Askaryan, which can be found in large volumes throughout the world, including in Romania. We have performed simulations of neutrino-nucleon charged-current and neutral-current interactions in the HERWIG code, in the $10^{12} - 10^{17}$ eV energy range and then injected all of the resulting particles in GEANT4 code, for the low energy primaries, and in AIRES code, for the higher energies. The calculation of the radio signal was performed considering the entire shower evolution, by taking into account in the equations 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 registering the radio emission from the showers they initiate.

Key words: Radio emission, neutrino induced showers in salt, HERWIG, GEANT4, AIRES.

1. INTRODUCTION

The emission of radio waves from high energy particles at their passage through a medium is called the Askaryan effect and is based on calculations made by Askaryan starting with 1961 [1, 3]. 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 is registered.

In dense media, such as ice, sand and salt (proposed by Askaryan in 1965

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[2, 3]), the length of the shower in the material is of the order of a few meters. Thus the electromagnetic radiation in the radio and microwave 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.

Applicability of the radio technique for detection of energetic particles, cosmic rays and astrophysical neutrinos, employing the Askaryan effect is an important question. As long as the power of the radio signal scales with the square of the number of particles generating it (because of coherence, at low frequencies), detection of emission from showers is measurable given that the primary energy of the incident particle is at least of the order of $\sim$ PeV. The best candidates for this type of detection are astrophysical neutrinos.

For the present study we have chosen rock salt as the detection medium. Salt is found close to the surface in domes throughout the world, but, being naturally occurring, each site must be sampled and analyzed because no two sites are the same and even minor differences induce effects in the transmission of the signal. Salt has been tested for radio transmission in different locations [4] and found to be satisfactory for detection at small distances. Some preliminary transmission tests have also been performed on the Slanic Prahova rock salt in Romania [5] and other physical investigations have been performed [6, 7].

2. RADIO EMISSION IN DENSE MEDIA

In the following study we will use the longitudinal profile of the shower to calculate the radio signal, as in [8, 9].

Charges of opposite sign which radiate coherently will give electric fields that cancel. It is only the charge excess that determines the net field in the radio domain. The compact approach takes into account only the spatial distribution of the charge. Here we will consider only the longitudinal profile.

The derivation of the equations for the calculation of the electric field starts from the retarded potentials and, following the calculations described in [8] with the Fraunhoffer approximation, in the frequency domain, we come to the equations:

$$\vec{E}(\vec{x},\omega) = \frac{e\mu_r}{2\pi\epsilon_0 c^2} i\omega \frac{\vec{v_\perp}}{v} \frac{e^{ikR}}{R} \int_{-\infty}^{\infty} dz' q(z') e^{i\frac{\omega}{c}(1-ncos\theta)z'}, \tag{1}$$

for the case when only the longitudinal profile, $q(z)$, is used.

In the time domain the vector potential far from the Cerenkov angle is written as:

$$\vec{A}(\vec{x'},t') = \frac{\mu e}{4\pi} \vec{v}_\perp \frac{1}{R} \frac{1}{|1-\frac{vn}{c}cos\theta|} q(\Lambda) \tag{2}$$

and the electric, using the longitudinal profile, $q(\Lambda)$, is:

$$\vec{E}(\vec{x'},t') = -\frac{\mu}{4\pi}\frac{e}{R}\vec{v}_{\perp}\frac{v}{|1-\frac{vn}{c}cos\theta|(1-\frac{vn}{c}cos\theta)}\frac{\partial q(\Lambda)}{\partial \Lambda}, \quad (3)$$

where Λ is defined as $\Lambda = \frac{v(t-\frac{nR}{c})}{1-\frac{vn}{c}cos\theta}$.

3. FIRST INTERACTION OF NEUTRINOS

Common shower simulation codes, like GEANT4 of AIRES, do not have the capability to simulate neutrino interactions; neutrinos are only transported through the medium. In order to study the realistic case of a neutrino interacting in salt and generating a radio signals we simulate the first interaction in an external event generator. For this we have the Fortran based HERWIG 6.5 code [13]. One of the reasons we have chosen HERWIG, besides accepting neutrinos as input and describing their interactions, is that it is used together with the CORSIKA code [11] for the simulation of neutrino induced showers in the atmosphere, which is know for correctness and reliability. We have performed simulations up tot 10^{17} eV, in the range where the parton distribution functions don't need extrapolation [12].

With the HERWIG code we have simulated all charged current (CC) and neutral current (NC) neutrino-nucleon interactions at primary energies of 10^{12} eV, 10^{15} eV and 10^{17} eV.

As the energy of the primary neutrino increases the energy carried away by the corresponding lepton in a CC interaction increases reaching up to 50% for 10^{17} eV primary energy. The types of particles generated in this first interaction vary from leptons to mesons and hadrons, from up to 15 for the lowest energy and up to ~ 80 for the highest input energy.

4. GEANT4 AND AIRES NEUTRINO-INDUCED SHOWER SIMULATIONS

The particles generated in the first neutrino interactions, using the HERWIG code, are subsequently injected into GEANT4 or AIRES codes, depending on their energy. GEANT4 [14] has an energy threshold of 10^5 GeV, and, therefore, we injected into this code only the particles resulted from the 10^{12} eV first neutrino interaction. For the cases where the primary has 10^{15} or 10^{17} eV energy we use the AIRES code [15] with the TIERRAS package [16]. Due to the fact that the AIRES code doesn't recognize all types of incident particles, only the stable ones, we have decayed all the unstable particles, in advance, using a simple GEANT4 decayer.

In order to analyze the profiles we split the resulted events in classes according to the energy carried away by the corresponding lepton for the CC interactions and carried away by the rest of the secondary particles besides the neutrino in an NC

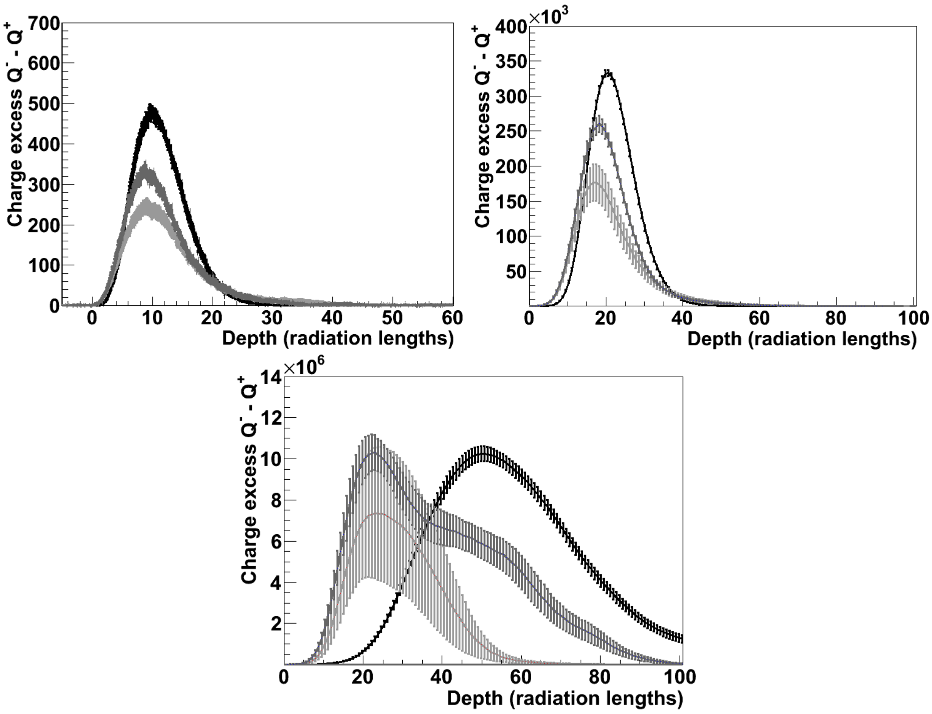

Fig. 1 – Longitudinal profiles for $\nu_e + p$ showers at 10^{12} (*top, left*), 10^{15}, (*top, right*) and 10^{17} (*bottom*), eV primary energy, for classes 1 (*light gray*), 5 (*gray*) and 10 (*black*). Error bars are standard errors.

interaction; class 1 means the lepton carries (0.1$\pm$1%) E_0, class 5 means the lepton carries (0.5$\pm$1%)E_0 and so on. For the ease of representation we will display classes 1, 5 and 10.

Figure 1 shows longitudinal profiles of showers resulted from the $\nu_e + p \rightarrow e^- + X$, simulated for 10^{12}, 10^{15} and 10^{17} eV primary energy. The width of the line comes from the standard error.The longitudinal profile is represented as number of particles *vs.* depth in radiation lengths ($1X_0$=10.09 cm).

The charge excess, that contributes to the generation of the radio waves, is found to be in the range 20-25 % of the number of particles at the shower maximum, for all the simulations, with the lower values for the lower energies.

5. RADIO SIGNAL FROM GEANT4 AND AIRES NEUTRINO-INDUCED SHOWERS SIMULATIONS

Using the profiles averaged to each class of showers and the equations (1), (2) and (3) we have calculated the electric field emitted by a neutrino-induced shower in salt.

For the GEANT4 simulations, because we have detail to all the information on the particles, we compute the average β factor, which is $\sim$ 0.9, and not 1. For the AIRES simulations, not having access to particle information and the primary energy being higher, we take $\beta = 1$.

Due to limitation of this text we present only $\nu_e + p \rightarrow e^- + X$, CC interaction. All the figures can be found in [17]. Figure 2 shows, for CC interaction showers simulated at 10^{12}, 10^{15} and 10^{17} eV, the dependence of $R|E(x,\omega)|$ on the angle of observation, and frequency, and figure 3 shows the electric field and vector potential in the in the time domain.

6. CONCLUSIONS

We have performed simulations of neutrino induced showers in salt using GEANT4 for 10^{12} eV primaries, and AIRES codes for 10^{15} and 10^{17} eV primaries, of charged-current and neutral current neutrino-nucleon interactions induced showers in salt.

For the GEANT4 10^{12} primaries simulations, having access to information on each particle, we could compute and use the average β which is ~ 0.9. This $\beta \neq 1$ induces differences in the pulses for $\theta_C \pm 5^0$, the pulse in time is shortened and the pulse is higher, as seen in figure 3 (a). For the AIRES simulations, at 10^{15} and 10^{17} eV, we have used $\beta = 1$. There is still an amplitude asymmetry between the pulses before zero reference time (inside the cone) and above zero (outside the cone) due to the term $1 - \beta n cos\theta$ in both A and $R|E|$ equations. The pulse outside the cone last for $\sim$ 2 ns for 10^{12} eV and up to $\sim$ 10 ns for 10^{17} eV. In the time domain the depth of the shower in the material is responsible for the spread in time of the signal and the amplitude of the profile (number of particles in excess) for the amplitude of the signal. As the signal in salt is shorter than in materials of lower density the pulse is also shorter. For the calculations performed in the frequency domain we also observe that the width of the dependence $R|E(\nu,x)|$ *vs.* observation angle varies between 6 and 10 degrees and the frequency dependence shows no frequency cutoff for the lower energies, in the range 1-10 GHz.

In the frequency domain, for the CC interactions, we observe that the simulations for antineutrinos tend to have the same behaviour as for the corresponding neutrinos. For the CC interactions the ν_p and $\tilde{\nu}_p$, which produce an electron/positron generate predominantly electromagnetic showers. For ν_μ and $\tilde{\nu}_\mu$, as the energy (class) increases the muon carries more energy and dissipates it in small amount along a longer trajectory. In the case of the tau lepton, the difference between the classes is insignificant for 10^{12} and it increases with energy. But for the NC interactions we observe that the energy transfer is important and not the type of neutrino because regardless of the primary neutrino in an NC interaction the shower that is generated is a mixed one, with no preferential energy transfer to one type particle.

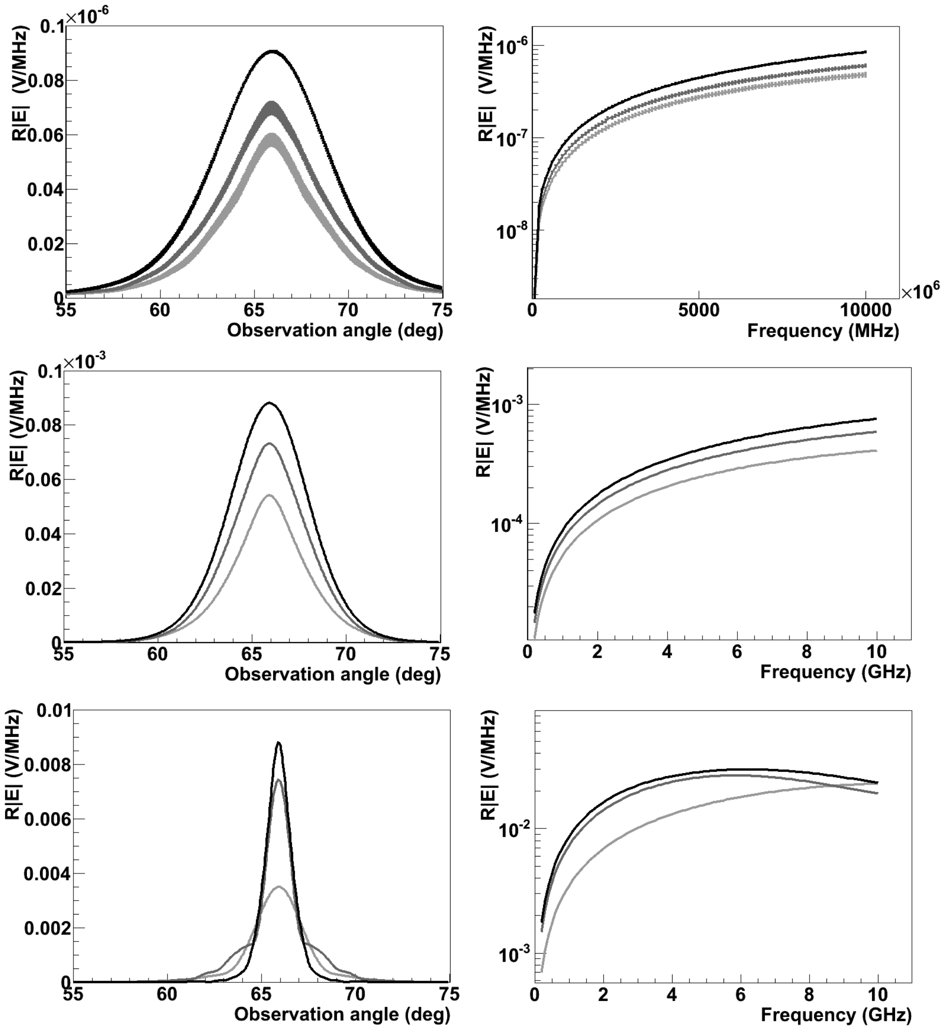

Fig. 2 – $\nu_e + p \rightarrow e^- + X$. Angle dependence for a frequency of 1 GHz (*left*), and frequency dependence at the Cerenkov angle (*right*), of $R|E(\vec{x},\omega)|$ (V/MHz), in CC neutrino-nucleon interactions for 10^{12} eV (*top*), 10^{15} eV (*middle*), and 10^{17} eV (*bottom*), primary energy, for classes 1 (*light gray*), 5 (*gray*) and 10 (*black*).

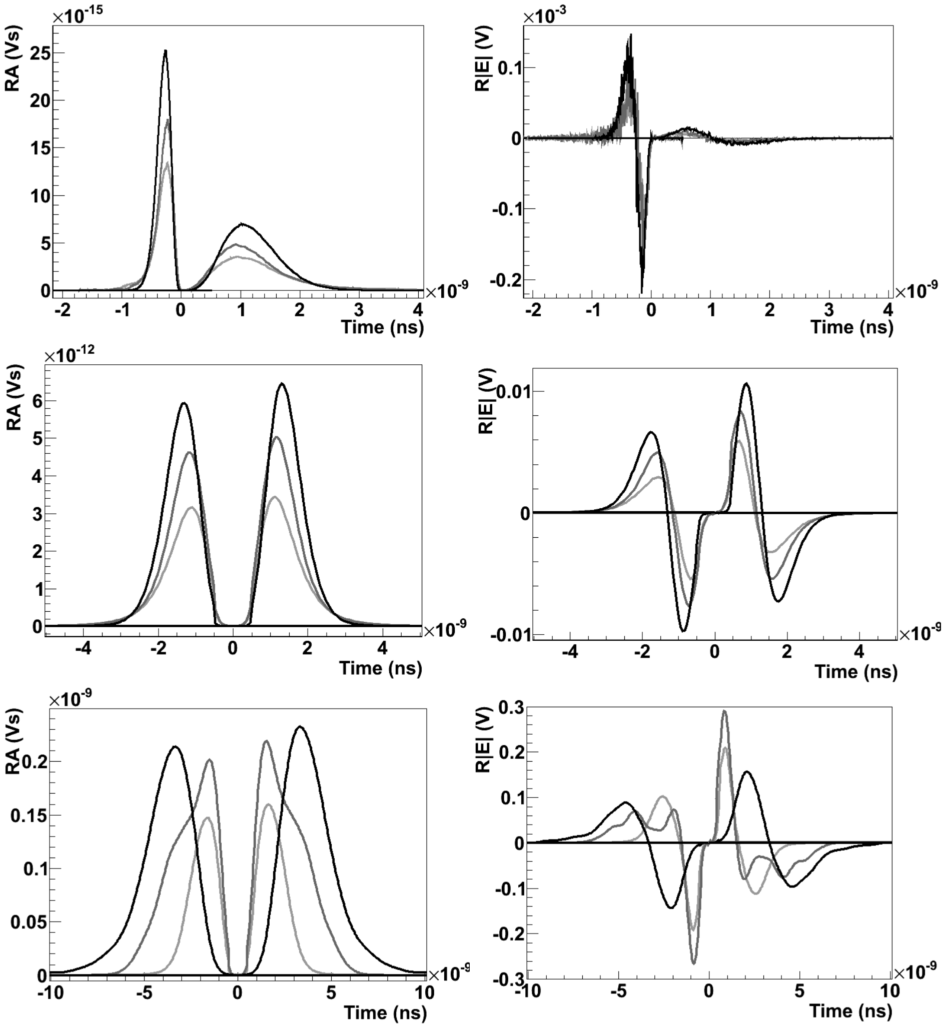

Fig. 3 – $\nu_e + p \rightarrow e^- + X$. Vector potential (*left*) and electric field (*right*) in CC neutrino-nucleon interactions for 10^{12} eV (*top*), 10^{15} eV (*middle*), and 10^{17} eV (*bottom*), primary energy, for classes 1 (*light gray*), 5 (*gray*) and 10 (*black*).

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