

On the importance of electron neutrinos in radio Cherenkov experiments.

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Abstract. Numerous experiments - RICE, ANITA, LUNASKA, NuMoon - are looking for EeV-ZeV neutrinos using the coherent radio emission generated upon their interaction in a dense medium (the Askaryan effect). Despite the electromagnetic cascades resulting from an electron neutrino undergoing a charged-current interaction being of comparable energy to that of the initial particle, their contribution to the total event rate is expected to be largely suppressed due to the Landau-Pomeranchuk-Migdal (LPM) effect. In this contribution, we use ‘thinning techniques’ to simulate electromagnetic showers of energies up to 100 EeV, minimising computing time while keeping a good level of accuracy. We use these simulations to give a description of the *secondary peaks* in the radiated spectrum of LPM showers around the primary maximum. These peaks have not generally been considered when computing the sensitivity of radio Cherenkov experiments. They are potentially important for the detection of electron neutrinos.

Keywords: UHE ν detection, Cherenkov radiation

I. INTRODUCTION AND MOTIVATION

The search for ultra-high energy (UHE) neutrinos – at EeV-scale energies and above – is one of the most interesting challenges in experimental astroparticle physics. The detection of UHE ν s is motivated by observations of the highest-energy cosmic rays. It is believed that neutrinos should be produced together with ultra-high energy cosmic rays in interactions at the sources and/or when propagating through the Cosmic Microwave Background radiation field [1], [2]. UHE ν s are also expected in top-down scenarios in the decay of super-massive particles produced in the early Universe, with expected fluxes harder than those believed to be produced in cosmic ray interactions [3]. Their detection will help identifying the sources of cosmic rays at UHE, as well as providing insight into UHE astro- and particle-physics.

Although in both acceleration and top-down mechanisms a proportion $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$ is predicted, it is reasonable to expect a ratio of $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$ at Earth due to neutrino oscillations with maximal mixing after the neutrino flux has travelled over cosmological distances.

A very promising method to detect high-energy particle interactions was proposed in the 1960’s by G. A. Askaryan [4]. The idea is to remotely detect the coherent Cherenkov radiation produced from the excess of electrons in the cascade of particles resulting from a high-energy particle interaction in a dense medium transparent to radio waves. In dense media (density $\sim 1 \text{ g cm}^{-3}$) the coherence extends up to the GHz frequency range. As the power in the coherent radiation scales with the square of primary particle energy, this method is particularly suitable for the detection of the highest energy ν s and cosmic rays, in a cost-effective manner without densely instrumenting large volumes of target material. Starting from the pioneering experiment using the lunar Cherenkov technique at the Parkes radio telescope [6], the experiments (both present and planned) encompass the Antarctic in-situ ice experiment RICE [5], a balloon experiment ANITA [7], and lunar Cherenkov experiments using radio telescopes both ground-based, GLUE [8], NuMoon [9] and LUNASKA [10], and in lunar orbit, LORD [11].

A. Aim of this work

The angular distribution of the emitted electric field around the neutrino-induced shower axis exhibits a characteristic multi-peaked pattern with a central peak at the Cherenkov angle. This structure can be understood by exploiting the analogy with diffraction by a single slit by Fourier-transforming an approximate longitudinal and lateral profile of the shower [12], [13], [14]. The angular width of the pulse reduces significantly in showers induced by high-energy electrons or photons – above typically 10-100 PeV in dense media [15] – due to the Landau-Pomeranchuk-Migdal effect [16], which stretches the induced electromagnetic showers in the direction along the shower axis [17], [18], [19]. For instance a 10 EeV electromagnetic showers produces a pulse which is 10 times narrower than at PeV energies. The LPM effect is not so important in hadronic showers at EeV energies because of the large multiplicity of the first interactions which reduces significantly the energy of the secondaries. Moreover, above a few PeV π^0 s – which typically feed the electromagnetic component of the shower when they decay into photons – are more likely to interact in dense media than to decay, further reducing the energy of the secondary photons below the

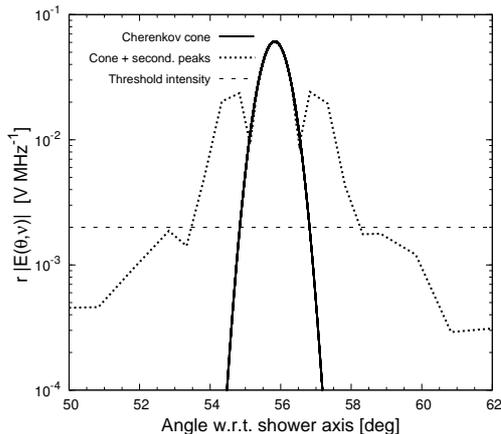


Fig. 1. Angular distribution of coherent Cherenkov radiation calculated for electron-induced showers in ice at 10 EeV primary energy at a frequency of 350 MHz (dotted line). The solid line is a Gaussian fit to the Cherenkov cone. The dashed line is the threshold electric field intensity used in this work for the purposes of estimating the relevance of the secondary peaks that appear away from the Cherenkov angle in showers strongly affected by the LPM effect.

LPM energy scale. As a consequence the angular width of the peak around the Cherenkov angle decreases only logarithmically with shower energy. These effects have been studied in [12], [20].

Neutrino showers can be of hadronic and mixed character. The first case corresponds to neutral current (NC) interactions induced by all flavor ν s or to charged current interactions induced by muon neutrinos, in which on average 20% of the energy is carried by the hadronic shower at ultra-high energy. Mixed showers are induced in charged current (CC) electron neutrino interactions and are composed of a purely electromagnetic shower – produced by an energetic electron carrying on average $\sim 80\%$ of the energy of the neutrino – and a hadronic shower initiated by the debris of the interacting nucleon. In this type of interactions all the neutrino energy is channeled into the resulting shower and for this reason ν_e are expected to contribute significantly to the total neutrino event rate. Despite this fact and due to the LPM effect as explained above, the electron neutrino rate is expected to be suppressed due to the strong narrowing of the Cherenkov peak which reduces the solid angle for observation.

However at ultra-high energies other peaks besides the so-called *Cherenkov cone* appear in the diffraction pattern. These *secondary peaks* in the radiated spectrum of LPM showers around the primary maximum can increase the solid angle of observation and can enhance the ν_e event rate. These peaks have not generally been considered when computing the sensitivity of radio Cherenkov experiments which typically use parameterisations of the Cherenkov cone as given in [21], [22]. An example is shown in Fig. 1 where the angular distribution of a 10 EeV purely electromagnetic shower is shown. The secondary peaks surrounding the Cherenkov cone are clearly visible and are higher than

the minimum detectable field strength. For comparison the parameterisation of the Cherenkov cone is also shown.

The main aim of this contribution is to estimate the importance of the secondary peaks in the diffraction pattern for the detection of UHE ν_e -induced showers. Although this study could be relevant for estimates of the exposure of a variety of experiments, we have concentrated on the effect of the secondary peaks on the detection of ν_e -induced showers with an array of antennas buried in ice.

II. APPLICATION TO NEUTRINO DETECTION WITH AN ARRAY OF ANTENNAS BURIED IN ICE

A variety of experiments using the radio technique are sensitive to UHE ν_e . Among them are those using the Moon or the ice cap at the South Pole as a target where neutrino interactions can be detected. We have devoted this work to the estimate of the potential enhancement of the sensitivity to ν_e of an array of antennas buried in the ice at the South Pole.

We have determined the ν_e detection efficiency by means of a dedicated Monte Carlo simulation of the propagation of the radio signal in ice, from the neutrino interaction vertex to the positions of the receivers. To make our estimate more realistic we use the positions of the 16 radio receivers of the Radio Ice Cherenkov Experiment (RICE) buried in the ice cap at the South Pole at depths ranging from ~ 100 m to ~ 350 m [5]. Neutrino interaction vertices are chosen randomly inside a cube of size $2 \times 2 \times 2$ km³. Arrival directions are taken to be isotropically distributed around the position of the array. Electron neutrinos are assumed to induce a purely electromagnetic shower carrying $1 - \langle y \rangle \sim 0.8$ of the energy of the neutrino, where $\langle y \rangle E_\nu \sim 0.2 E_\nu$ is the average energy transferred to the hadronic vertex which we neglect in this study.

The simulation of the electric field strength around the Cherenkov angle is based on the well-known ZHS code [23]. Full calculations of coherent Cherenkov radiation from simulated electromagnetic cascades are very computationally intensive. Particles have to be tracked down to sub-MeV energies where the bulk of the radiation is known to be produced [23], so that tracking all 10^{12} particles expected in a single EeV shower is infeasible with current technology. For this purpose we have applied thinning techniques in the ZHS code described in [22], which have been shown to reduce very significantly the computer time, while at the same time keeping a good accuracy between full and thinned simulations. Thinning techniques involve following only a small, representative fraction of the particles in a shower, and assigning to each tracked particle a corresponding weight to compensate for the rejected particles. In [22] it has been shown that there is a remarkable agreement between the frequency spectrum of the electric field as obtained in full and thinned Monte Carlo simulations of showers in different media.

We have simulated 25 individual electromagnetic showers per energy bin with energies ranging from $E = 10$ PeV to 10 EeV in steps of 0.5 in $\log_{10} E$. For a fixed energy each time a neutrino vertex and direction of propagation is generated we randomly sample one shower out of the 25 simulated. This accounts for the large shower-to-shower fluctuations expected in LPM showers [18], [19]. The relative angle between the shower axis and the receiver is calculated and the signal is read directly from the sampled shower and propagated to each receiver taking into account its attenuation when travelling from the ν vertex to the antenna. We have used a model for the frequency-dependent attenuation length in ice at a fixed temperature of -50 C [5].

We have estimated the trigger probability in two different manners: accounting for the secondary peaks in the emitted electric field, and without accounting for them using a Gaussian parameterisation of the Cherenkov cone in the whole angular range around the Cherenkov angle. An example of the two descriptions of the electric field is shown in Fig. 1. A trigger in an antenna is assumed to occur if the electric field intensity at its position is above a fixed intensity threshold. Only for the purposes of illustration of the importance of the secondary peaks in detection, we have chosen the threshold so that the electric field emitted by a 30 PeV electromagnetic shower at the Cherenkov angle in ice, observed at a frequency of 350 MHz with a bandwidth of ± 150 MHz can be detected from a distance of 1 km. We have restricted ourselves to an angular range of $\pm 15^\circ$ around the Cherenkov angle, neglecting the contribution of the electric field at angles outside this range. We require at least 4 triggered antennas to have an ‘‘event trigger’’, and for each of these we count the number of antennas above threshold (event multiplicity).

Our Monte Carlo does not account for many effects that largely influence the absolute value of the detection efficiency (trigger probability) such as temperature-dependent attenuation length of radio waves, dependence of the refractive index of ice on depth, discontinuities in the ice cap, antenna gain and directionality, etc. Moreover, we have not made any attempt to perform a detailed simulation of the electronics of the experiment, radio signal processing, etc. However, we expect many of these effects to play a similar role in the detection efficiency estimated with and without accounting for the secondary peaks, and hence we expect many of them to cancel out when performing the ratio of efficiencies. For this reason we have chosen to compute the relative efficiency normalized to the ν_e trigger probability calculated at 10 EeV accounting for the secondary peaks in the angular distribution.

We have simulated 10^6 neutrino vertices for each neutrino energy. The relative efficiencies are shown in Fig. 2 as a function of neutrino energy. For neutrino energies below about 100 PeV there is no gain in trigger efficiency when accounting for the secondary peaks, the reason being that at these energies the LPM effect does

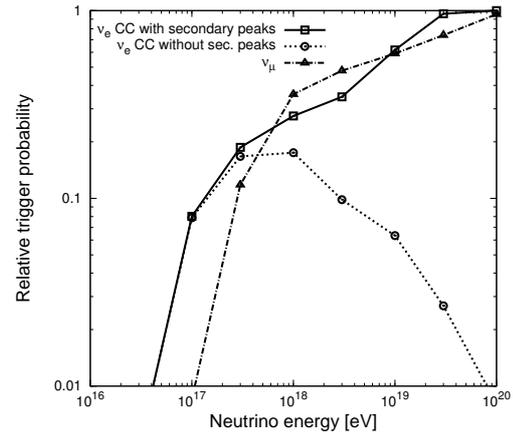


Fig. 2. Relative trigger efficiency of an antenna array with the receivers located as in the RICE detector. The relative efficiency is shown as a function of neutrino energy and is defined as the trigger probability normalized to the probability of detecting a ν_e with energy 10 EeV when accounting for the secondary peaks in the angular distribution of the electric field at 350 MHz. Solid line: Relative trigger probability for ν_e CC detection when the secondary peaks in the angular distribution are taken into account. Dashed line: relative trigger probability for ν_e CC detection when only the Cherenkov cone is accounted for in the simulations (see an example in Fig. 1). Dotted line: relative trigger probability for ν producing a hadronic shower only, i.e. ν of any flavour interacting through NC or ν_μ interacting through CC interactions.

not significantly shrink the Cherenkov cone. For energies above 100 PeV the gain increases dramatically with energy reaching a factor ~ 10 at 10 EeV. For the purpose of estimating the importance of the enhancement in the detectability of ν_e CC interactions when accounting for the secondary peaks, we have also calculated the relative efficiency of hadronic showers initiated by NC interactions of ν_s of any flavour or CC interactions of muonic neutrinos, assuming the shower carries on average 20% of the neutrino energy. In Fig. 2 we show this efficiency for a single neutrino flavour. We have checked that since hadronic showers do not suffer strong LPM effects the enhancement when calculating the efficiency with and without the secondary peaks is negligible as expected. One can see that above ~ 1 EeV the ν_e CC channel contributes essentially the same as the ν_μ CC channel. Clearly the larger width of the Cherenkov cone in the hadronic shower when compared to that in an electromagnetic one, compensates for the reduced energy carried by the shower. Since there are 3 flavours of ν_s and the cross section for NC interactions is roughly 2.5 times smaller than the cross section for CC interactions, we expect the 3 NC interactions altogether to contribute roughly the same as the ν_e CC channel. Adding the contribution of the ν_μ and ν_τ CC interactions (neglecting the contribution of the τ lepton produced in ν_τ CC interactions), we estimate that ν_e account for $\sim 20\%$ of the total event rate expected in an array of antennas at the highest energies.

‘‘Upward-going’’ ν_s with nadir angles between $\theta_{\text{nadir}} = 0^\circ$ and 90° are absorbed in the Earth at

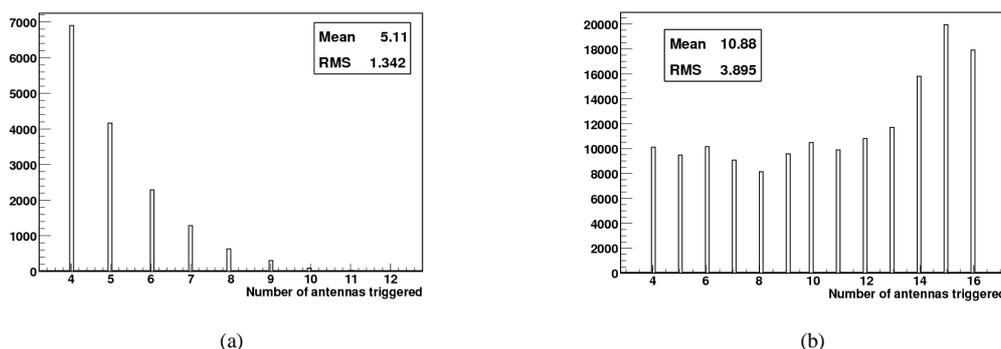


Fig. 3. (a) Number of antennas triggered by ν_e -induced showers at 10 EeV and central frequency of 350 MHz, when the secondary peaks in the angular distribution are not taken into account, i.e. only the central peak as shown in Fig. 1 is accounted for. (b) Number of antennas triggered in the same conditions as in panel (a) when the secondary peaks in the angular distribution are taken into account.

ultra-high energies. We have repeated our simulations for “down-going” ν_s only ($\theta_{\text{nadir}} > 90^\circ$) for which absorption in the Earth is much less important, and the relative efficiencies remain essentially unchanged.

In Fig. 3 we show the distribution of the number of antennas triggered for the cases without (left panel) and with secondary peaks (right panel) for ν_e CC interactions at 10 EeV. The wider angular distribution of the electric field when accounting for the secondary peaks induces events with a larger multiplicity as can be seen in the figure. The number of antennas triggered is somewhat dependent on many aspects of the detector not included in our simulations, but the plots serve to illustrate the enhancement induced when accounting for the secondary peaks. It is important to remark that a large multiplicity of triggered antennas may improve the efficiency in the reconstruction of the neutrino interaction vertex and direction, which is of great importance for background rejection in this type of experiment [5].

III. CONCLUSIONS AND OUTLOOK

We have shown that the detectability of ν_e CC interactions is greatly enhanced when the secondary peaks produced in the angular distribution of the emitted electric field is accounted for in the simulations. In the case of neutrino detection with an array of antennas buried in ice, both the trigger probability and the multiplicity of triggered antennas increases significantly with respect to the case in which only the Cherenkov cone is accounted for in the simulations. The secondary peaks may also play an important role in the detection of UHE ν_s with experiments using the Moon as target [24] and/or in experiments using antennas carried by balloons high in the atmosphere [7]. The potential enhancement in exposure achieved in these cases requires further evaluation.

IV. ACKNOWLEDGMENTS

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