Radiodetection of Neutrino Interactions in Ice.

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Abstract

We study the Cherenkov radio pulses emitted in PeV and EeV neutrino interactions in ice. We discuss how the rich radiation pattern in the 100 MHz to 1 GHz frequency range, in principle, allows the measurement of shower elongation produced in neutrino interactions opening up the possibility of flavor recognition through the identification of charged current electron neutrino interactions.

1 Introduction

High energy neutrino detection is one of the most attractive challenges for the next millennium. EeV neutrino fluxes are unavoidable in the production of the highest energy cosmic rays and their interactions with the Cosmic Microwave Background. There are several experimental efforts to construct Cherenkov detectors under water or ice with typical sizes of the order of $1\ \mathrm{km}^3$. The detection of high energy neutrinos could test models of acceleration and propagation of the highest energy cosmic rays. Moreover it can probe unexplored regions in the parameter space for neutrino oscillations. The expected neutrino fluxes are however low and could need very large installations. In this context it is worth exploring alternative techniques such as horizontal showers or the detection of Cherenkov radio pulses from neutrino interactions which could definitely provide complementary information to muon underground detectors.

The radio technique was proposed in the late fifties (Askar'yan 1962) as a possible means for detecting high energy showers. When the wavelength of the emitted radiation is greater than the physical shower dimensions, the emission from all particles is coherent and the electric field becomes proportional to the excess charge and hence to shower energy. The power radiated in radio thus scales with the square of the shower energy making the technique most attractive for detecting showers of the highest energies. Radio pulses have been observed in air showers but systematic studies are prevented by the influence of distant atmospheric phenomena which are difficult to control. This is not expected to be a problem for the detection of high energy showers produced by neutrinos in denser media because the showers are reduced by the density fraction and charge excess in the shower is then expected to be the dominant production mechanism for radio pulses. Ice has been proposed as an appropriate medium because of its large attenuation length for radio signals ($\sim$ 1 km) (Markov 1986, Ralston 1989) and efforts are being made to test its viability in Antarctica (Allen 1997). Among the potential advantages of the technique are the relatively low cost of the detectors (antennae) and most importantly the fact that information about the development of the excess charge in the shower can in principle be recovered from the rich diffraction pattern produced. In this work we calculate the different patterns produced by charged current electron neutrino interactions compared to the rest as a way to illustrate the potential of searching for coherent radio pulses. We briefly address the strategies to obtain information from an array of antennas.

2 Cherenkov radiation from neutrino showers

When an electron neutrino interacts with a nucleus through a charged current deep inelastic interaction (DIS), it produces an electron which initiates an electromagnetic shower while simultaneously a hadronic shower is initiated by the nuclear fragments. While these interactions produced "mixed" showers, in neutral current interactions of any flavor neutrinos and in charged current interactions induced by muon neutrinos only the hadronic shower is expected. We have previously shown that at high energies the Landau-Pomeranchuk-Migdal (LPM) effect affects electromagnetic (Alvarez 1997) and hadronic (Alvarez 1998, Alvarez 1999) showers in quite different ways.

The LPM manifests as a dramatic reduction of the pair production and bremsstrahlung cross sections at energies above $E_{\rm LPM}$ (2 PeV in ice) due to large scale correlations in the atomic electric fields. It dramatically elongates the development of electromagnetic showers in ice for energies above 20 PeV (Alvarez 1997). This can be quantified by an increase in shower length [1] proportional to $E_0^{1/3}$, where E_0 is shower energy. EeV hadronic showers initiated in neutrino interactions are less affected by the LPM effect (Alvarez 1998, Alvarez 1999). Below 1 EeV they do not display the typical elongation due to the LPM, while only a fraction of showers with energy above 1 EeV, show LPM tails which typically contain 10% of the shower energy.

The mixed character showers due to charge current electron interactions display the typical features due to the LPM effect as long as the electromagnetic component has an energy greater than 20 PeV. This depends on neutrino energy and on the energy transfer to the hadron debris. In Figs. 1 and 2 we show the longitudinal development of hadronic and mixed showers for neutrino energies 100 PeV and 10 EeV, and fractions of energy $y = 0.2$ and $y = 0.8$ respectively. The differences between the mixed and hadronic showers become evident as both the neutrino energy and the fraction of energy transferred to the electromagnetic component increase.

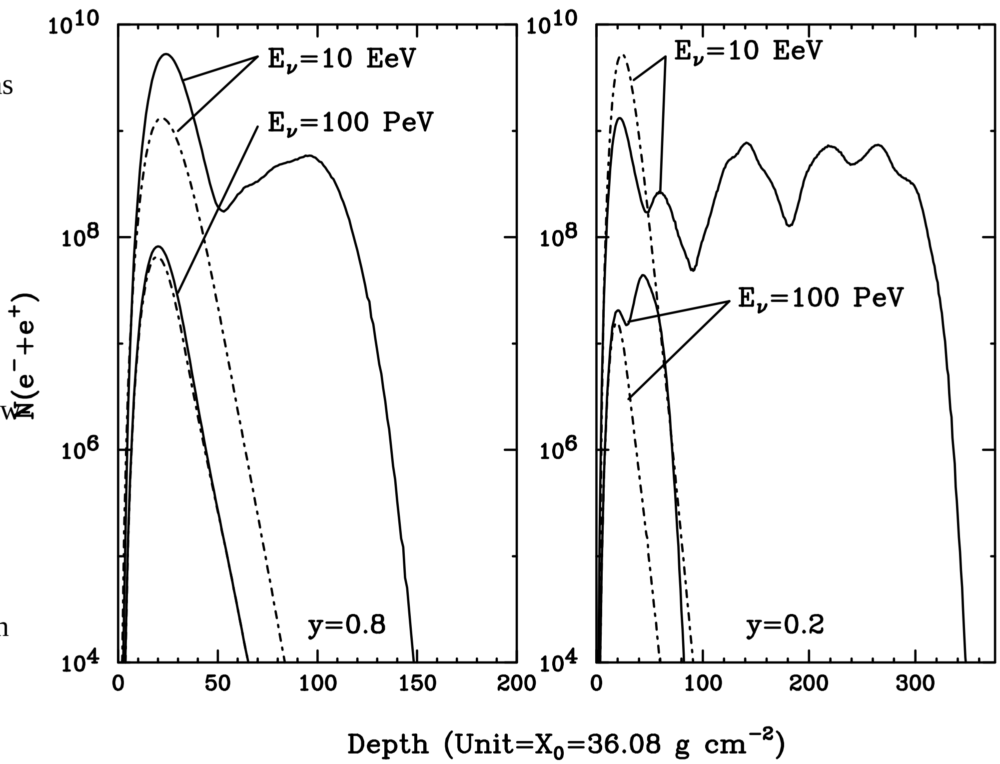

Figure 1: Longitudinal development of hadronic (dashed lines) and mixed showers (continuous lines) initiated by neutrino interactions in ice for different values of neutrino energies and y, as marked.

All the charged particles in the shower that travel at a speed greater than the speed of light in the medium contribute to the emission of Cherenkov radiation. When the wavelength is in the optical regime, the radiation is emitted incoherently. The output power is proportional to the total tracklength and hence to shower energy but in the radio regime the electric field amplitude is proportional to the excess charge in the shower because of coherence. In this case the electric field spectrum at a fixed frequency considered as a function observation direction exhibits a diffraction pattern which resembles that of a slit with a maximum in the Cherenkov direction ($\theta_C = 56^o$ in ice). The width of the Cherenkov peak is inversely proportional to shower length and to the frequency.

For a given observation angle the frequency spectrum of the electric field rises linearly with frequency up to a maximum frequency at which coherence is lost. In the Cherenkov direction this maximum frequency is mostly due to the lateral structure of the shower while away from it, it is due to interference between different stages in shower development, i.e. to the longitudinal shower development. It can be shown that spectrum of the electric field amplitude close to the Cherenkov direction can be well approximated by the Fourier transform of the 1-Dimensional longitudinal development of the charge excess. We have made extensive checks to

[1] Defined as the length along which shower size exceeds 70% of its maximum.

confirm the validity of this approximation, comparing its results with those obtained with full simulations. This method has allowed the study of the angular distributions of the radio pulse spectrum using fast programs to calculate shower development for energies up to 100 EeV (Alvarez 1997, Alvarez 1998, Alvarez 1999).

In Fig. 2 we show the angular distribution of the Fourier transform of the electric field emitted by the same showers in Fig. 1. The electric field normalization is chosen to be one in the Cherenkov direction for the shower with highest electromagnetic content so that relative amplitudes are correctly plotted. As shower length only increases by $\sim$ 30% between 100 TeV and 10 EeV hadronic showers, the angular distribution narrows approximately in the same proportion, a hardly noticeable effect. For the mixed showers induced by charged current electron neutrino interactions the situation is quite different. If the electromagnetic component has an energy E_{em} exceeding 20 PeV, the peak narrows as $E_{em}^{1/3}$ (Alvarez 1999). As the average fraction of energy transferred to the nuclear fragments is expected to be about $< y >= 0.25$, the LPM effect due to the electromagnetic part will be typically apparent already for electron neutrinos of energy above ~ 30 PeV. These showers display a characteristic diffraction pattern from the superposition of narrow and wide patterns due to the electromagnetic and hadronic components respectively.

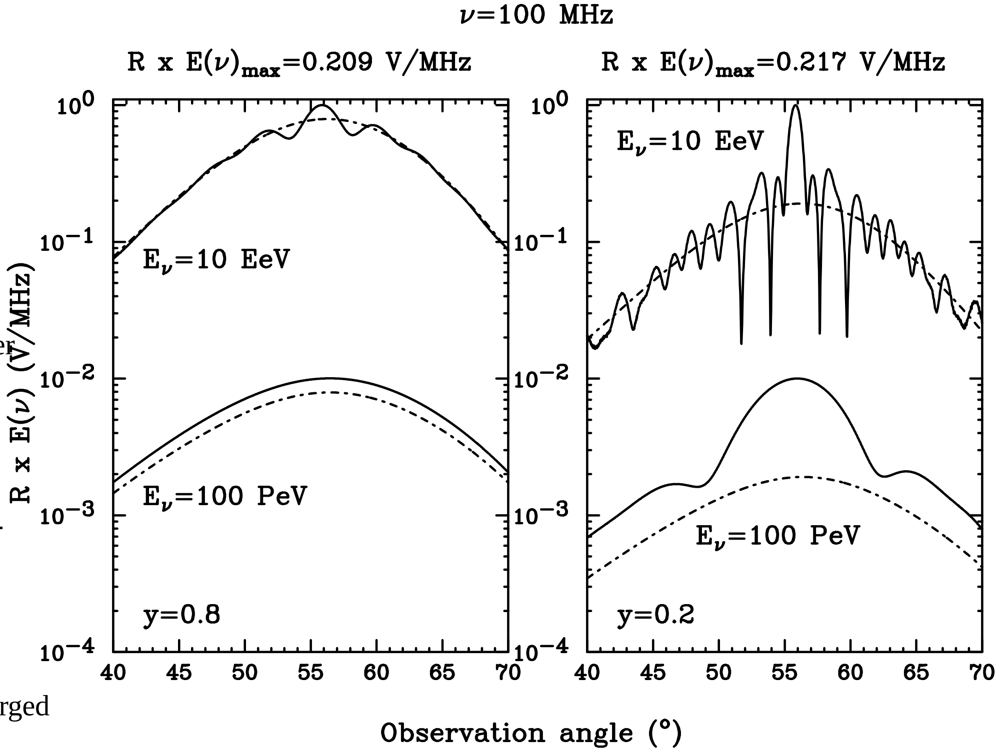

Figure 2: Electric field amplitude around the Cherenkov angle corresponding to the showers of Figure 1.

3 The potential of the radio technique

The radio technique has a large potential for high energy neutrino astronomy because of the rich structure of the electric field frequency spectrum and its angular diffraction. Information on neutrino interactions can be obtained with an array of antennas covering a large region and possibly using radiotelescopes pointing to the Moon (Dagkesamansky 1991, Alvarez 1997b, Gorham 1999).

The relative arrival times of the radio signals to four antennas allows the reconstruction of the radio emission source. Once the shower has been located the amplitudes measured in different detectors can be used to reconstruct the angular behavior of the electric field amplitude from which the shower direction is established ideally through the recognition of the direction of highest radiation, that is the region "illuminated" by the Cherenkov peak. Moreover the electric field amplitude measurement in the Cherenkov direction is proportional to the tracklength due to the excess charge in the shower and hence to the total electromagnetic energy in the shower. As distance to the shower is known the measurement allows an accurate determination of electromagnetic energy in the shower. If the width of the Cherenkov peak can be reconstructed then shower length should be established indicating whether there has been a significant elongation due to the LPM that is establishing whether high energy photons or electrons have been observed. This information can be converted to electron neutrino recognition provided the neutrinos have energies in excess of 30 PeV

There are however more ways to extract useful information from the interaction which can be considered as redundant but can be of extreme value for reducing spurious signals from other sources, what has been argued can be a serious problem for the technique. A suitable array of antennas should establish the Cherenkov cone region and from its geometrical shape both the shower position and orientation should become readily available. Cherenkov radiation is polarized in the direction of apparent movement of the excess charge and this can be very valuable (Jelley 1996). If the polarization of the signal is measured at three separate locations the emission source can also be located. The technique even allows obtaining a fair amount of information from a single site. The frequency spectrum of the electric field increases linearly with frequency until a maximum value which depends on the observation angle. Sampling the frequency spectrum at a single location allows the determination of the angle between the observation direction and the Cherenkov directions provided the shower is of hadronic type and in any case the amplitude measurements corresponding to the linear region of the spectrum also allow the determination of electromagnetic shower energy regardless of the type of shower in question.

In Figs. 1 and 2 we display the shower development and the corresponding angular distribution of the radio pulse spectrum. The figures illustrate the potential of the radio technique, and particularly how ν_e charged current interactions can be distinguished from neutral current interactions or charge current interactions of muon neutrinos. This is a characteristic of the radio technique due to its coherent character so that a wealth of information is carried by the rich diffraction pattern generated. In principle a simple inverse Fourier transform should allow the reconstruction of much longitudinal shower development what could be used to distinguish electromagnetic, hadronic and mixed type showers and hence opening up the possibility of flavor recognition. Surely the possibility would put much more stringent constraints on the design, rising its cost an complexity by large factors and this would have to wait till the technique is shown to be viable, however the wealth of information that could be obtained from such technique surely makes the effort worth its while.

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