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The strategy of discrimination between flavors for detection of cosmogenic neutrinos

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ABSTRACT

We propose a new method to identify flavors of ultra high energy cosmic neutrinos. Energy loss of leptons in matter provides important information for the detection of neutrinos originated from high energy astrophysical sources. About 50 years ago, Askaryan proposed to detect Cherenkov signals by radio wave from the negative charge excess of particle showers. The theory of Cherenkov pulses with Fraunhofer approximation was widely studied in the past two decades. However, at high energies or for high density materials, electromagnetic shower should be elongated due to the Landau–Pomeranchuck–Migdal (LPM) effect. As such the standard Fraunhofer approximation ceases to be valid when the distance between the shower and the detector becomes comparable with the shower length. We have performed Monte Carlo simulations recently to investigate this regime based on the finite-difference time-domain (FDTD) method, and modified time domain integration method. In this work, we adopt the deduced relationship between the radio signal and the cascade development profile to investigate its implication to lepton signatures. Our method provides a straightforward technique to identify the neutrino flavor through the detected Cherenkov signals.

1. Introduction

The nature and origin of ultra-high energy cosmic rays (UHECRs) have remained a mystery. These amazingly energetic events have been observed beyond $\approx 10^{19.6}$ eV, the so-called Greisen–Zatsepin–Kuzmin (GZK) [1] cut-off. The GZK feature on the UHECR spectrum has been first observed by the High Resolution Fly's Eye Experiment [2] and later confirmed by the Pierre Auger Observatory [3]. Above this energy scale, UHECRs interact with CMB photons through the GZK processes [1], producing cosmogenic neutrinos. The GZK feature on the cosmic ray energy spectrum guarantees the existence of the cosmogenic neutrinos. However, none of these have been observed so far. Detecting these ultra high energy (UHE) neutrinos provides critical information for unraveling the mystery of the origin and evolution of the cosmic accelerators and will be one of the utmost tasks in the coming decade [4].

One promising way of detecting UHE neutrinos is the radio approach. When an ultra-high energy cosmic neutrino interacts with ordinary matters on the Earth, it would lead to a hadronic debris, either by charged current or neutral current. The former also produces a lepton with corresponding flavor. Both the high energy leptons and the hadronic debris induce particle showers. As proposed by Askaryan in the 1960s [5], the high energy particle shower develops in a dense medium would have net negative charges. This charge imbalance appears as a result of the knocked-off electrons being part of the shower, as well as the positrons in the shower annihilating with the electrons of the medium. The net charges of the showers, typically 20% of total shower particles, serve as a source emitting the Cherenkov radiations when they travel in the medium. The sizes of the showers are quite localized (tens of cm in radial and few meters in longitudinal development) compared to those develop in the air (km scale), and therefore result in coherent radiations for wavelengths longer than the shower sizes. The corresponding coherent wavelength turns out to be in the radio band, from hundreds of MHz to few GHz.

In this paper, we discuss the possibility to identify the flavors of the cosmogenic neutrinos detected by the radio neutrino telescope, such as ANITA [6], Askaryan Radio Array (ARA) [7], and ARIANA [8].

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2. The strategy of flavor identification

As neutrinos interact with matters to produce observable signals, the major channel is the changed-current (CC) interaction. The electron produced through ν_e CC interaction has a large interaction cross-section with the medium and produces a shower within a short distance from its production point. Contrary to the electron, the muon produced through ν_μ CC interaction can travel a long distance in the medium before it loses all its energy or decays. However, a muon does emit dim light along its propagation so that only those detectors near to the muon track can be triggered.

As for ν_τ detection, the $\nu_\tau-$induced tau leptons behave differently at different energies for a fixed detector design. For a neutrino telescope such as IceCube, the observable energy range for the double bang event is 3.3 PeV $< E_\nu <$ 33 PeV. For an undersea experiment, such as KM3Net [9], the observable energy range for the double bang event is similar. But, for a radio neutrino telescope, such as ARA, the detector is designed to observe cosmogenic neutrinos of energy about EeV. In this energy regime, the tau lepton range becomes long enough so that a tau lepton can pass through the detector without decaying but losing its energy like a muon does. In this case, the signal for ν_τ appears like a track event.

Note that the lights emitted from the track can only trigger the nearby optical detectors. A different strategy is taken to construct track events for radio detectors. For cosmogenic neutrinos, the energy of the CC-induced muon or tau lepton is so high that a muon or tau lepton not only emits dim lights but also produce mini-showers along its propagation through the detector fiducial volume. By detecting the radio emissions from these mini-showers, a track event is reconstructed for a muon or tau lepton traveling through the detector. By observing a single shower, a ν_e signal is identified from a track event for a ν_μ or ν_τ.

It is challenging to distinguish between ν_μ and ν_τ signals because both muons and tau leptons produce similar track-like events. Simulation of lepton propagation in ice shows that the compositions of the mini-showers are different for muon and tau lepton track events. The mini-showers that consist of the track events are composed of two categories, electromagnetic (EM) and hadronic showers. The energy loss distribution between EM and hadronic showers is different for muon and tau lepton track events. A muon track event loses more energy through EM showers than through hadronic ones while a tau track loses more energy through hadronic showers than through EM ones. By collecting mini-showers, measuring their attributes and evaluating energy losses, one can distinguish between muon and tau track events.

3. Shower identification

ARA underground radiowave antenna stations receive radio emissions from shower particles created by cosmogenic neutrinos in ice. These radio signals are Cherenkov radiations produced by net charges of shower particles. We adopt COSIKA-IW [10,11] code, a modification of COSIKA [12] program for dense-target simulation, to simulate EM and hadronic showers. In Figs. 1 and 2, longitudinal developments of charges are shown for EM and hadronic showers respectively. We demonstrate the different characteristics between electron and proton induced showers in ice. The hadronic shower is simulated by a proton hitting a dense medium and evolves as a typical profile with one peak at the shower maximum. For the EM shower, however, the case is different. At energies higher than 10^{16} eV, bremsstrahlung and pair-production processes are suppressed by Landau–Pomeranchuck–Migdal [13] effect. As a result, cascades are stretched, shower development is elongated and several peaks appear in the shower longitudinal profile.

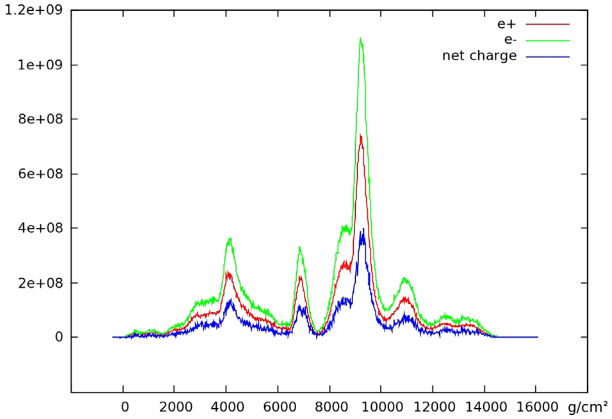

Fig. 1. Longitudinal profile of a 10^{19} eV electron shower in ice where the number of charged particles in the shower are shown. As LPM suppression increases with the square root of the energy, multiple peaks occur during the elongated shower development. The profile is sensitive to the initial interactions of the cascade.

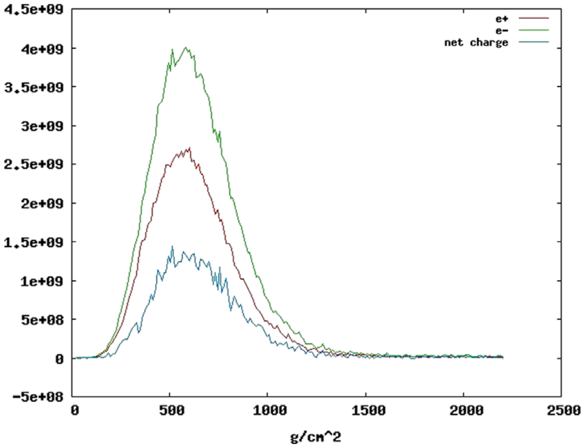

Fig. 2. Longitudinal profile of a 10^{19} eV proton shower in ice where the number of charged particles in the shower are shown. The hadronic shower is initiated by the cascade of mesons. The decay length of neutral pions is longer than the LPM interaction length in ice for electrons at energy 10^{15} eV. Meanwhile the secondary mesons produce very few electrons due to LPM suppression.

Cherenkov radiation induced by a rather complicated shower profile can be computed via the time-domain finite-difference (FDTD) method [14] and the time-domain integration method. Between the shower profile $\rho(x)$ and the radio signal $E(t)$ exists a one-on-one correspondence [15]. The electric field of Cherenkov radiation can be calculated by solving the inhomogeneous Maxwell equations, as it has been demonstrated by Alvarez-Muñiz et al. [16]. The vector potential can be conveniently obtained in Coulomb (transverse) gauge. The vector potential measured at the detector is then the integral of that contributed from every segment of the shower current, and in turn the electric field can be obtained from the vector potential, as follows:

$$\mathrm{A}_C(\mathrm{x},t) = \frac{1}{4\pi\varepsilon_0 c^2}\int dt' \frac{J(t',x')}{|x-x'|} \tag{1}$$

$$\mathrm{E}(\mathrm{x},t) = -\nabla\Phi(x) - \frac{d\mathrm{A}(\mathrm{x},t)}{dt} \tag{2}$$

where t' is the retarded time, x' is the position of the shower particles at retarded time, and x is the position of the detector, and J is the transverse current sources.