Propagation of Extremely High Energy Leptons in the Earth

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Abstract

It has been claimed that underground neutrino telescopes such as AMANDA and IceCube have detection capability of not only PeV neutrinos but EeV-ZeV neutrinos which are possibly generated by the GZK mechanism associated with the Highest Energy Cosmic Rays. The accurate calculations on propagation of neutrinos and produced muons and taus in the Earth is inevitable for realistic evaluation of such Extremely High Energy (EHE) neutrino detection possibilities, however. The relevant interactions involving EHE neutrinos and charged leptons include charged-current interactions contributing to charged lepton disappearance and the photo-nuclear interactions, both of which has not been considered or only evaluated by the cross sections without accounting newly available data of the photon-nucleon collisions. Here we present the results of the detailed numerical calculations concerning particle propagations at EHE energies (EeV or greater). We use the GZK neutrino flux as a benchmark and show the resultant energy spectra of EHE neutrinos after their propagation in the Earth as well as the generated secondary leptons. The expected event rate above 0.1 EeV by a km cube detector is ~ 1 event/year.

1. Introduction

It is well known that there exist extremely high energy (EHE) particles in the Universe with energies up to $\sim 10^{20}$ eV. These EHE cosmic rays may be originated and/or producing neutrinos by the various mechanism. Underground neutrino telescopes being operated and/or planned to be built are expected to detect such EHE neutrinos [1]. In their travel in the earth to the detection volume in a telescope, EHE neutrinos collide with nuclei in the rock due to enhancement of the cross section at EHE range and produce secondary leptons like μ and τ. The expected mean free path is $\sim 600(\rho_{rock}/2.65\mathrm{g\ cm}^{-3})^{-1}(\sigma_\nu/10^{-32}\mathrm{cm}^2)^{-1}$ km which is a far shorter than a typical path length of the propagation in the earth. Moreover, the decay lifetime is long enough at EHEs for the produced μ and τ to survive and possibly reach the detection volume directly. The resultant fluxes and spectrum of EHE particles are rather complex and the accurate understanding of the EHE neutrino and lepton propagation in the earth is inevitable for EHE

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neutrino search by the underground neutrino telescopes. Here we numerically calculate the intensity and the energy distribution of EHE neutrinos and their secondary produced μ's and τ's in the propagation in the earth. The results are shown for the GZK Neutrinos [2], generated from the decay of photopions produced by EHE cosmic ray protons colliding with the cosmic thermal background photons, since the GZK neutrino model is appropriate for a benchmark as the flux prediction is on the solid theoretical foundation.

2. The Relevant Interactions and the Calculation Method

An EHE neutrino is a subject to charged-current (CC) and neutral-current (NC) interactions with nucleon. As there is no direct measurement of the relevant interactions in EHE range, the predictions of the νN cross sections rely on incompletely tested assumptions about the behavior of parton distributions at very small values of the momentum fraction x. Since we do not have further clues to investigate EHE neutrino interactions in our hands, we limit our present analysis within the range of the standard particle physics and use the cross section estimated by the CTEQ version 5 parton distribution [3] functions.

μ's and τ's are the main products of the νN interactions. Electrons and hadrons are also produced, but they initiate shower cascades immediately in the rock and would not run over the long distance and their contribution to the overall EHE particle flux after the propagation is negligible. In EHE range, μ and τ are further interacting with nuclei (and atomic electrons) via pair creation, Bremsstrahlung, and the photopion production. The photopion production cross section has the largest uncertainty at EHEs due to the same reasons for the νN interactions. In this calculation is used the estimation based on the deep-inelastic scattering formalism with the ALLM parameterization of the structure function, which has been considered to be most reliable prediction. Furthermore, the week interaction, $l^{\pm}N \to \nu X$, to cause muon and tauon disappearances, and the heavier lepton pair production such as $\mu^+\mu^-$ are also taken into account in the present calculation, which leads to a visible contribution to the particle fluxes at EHEs.

The calculation of the intensity and energy distribution of propagating particles in the earth is carried out with numerically resolving the transport equations as

$$\begin{aligned}
\frac{dJ_\nu}{dX} &= -N_A\sigma_{\nu N,CC+NC}J_\nu + \frac{m_l}{c\rho\tau_l^d}\int dE_l\frac{1}{E_l}\frac{dn_l^d}{dE_\nu}J_l + N_A\int dE'_\nu\frac{d\sigma_{\nu N,NC}}{dE_\nu}J_\nu \\
&\quad + N_A\int dE'_l\frac{d\sigma_{lN}}{dE_\nu}J_l \\
\frac{dJ_l}{dX} &= -N_A\sigma_{lN}J_l - \frac{m_l}{c\rho\tau_l^d E_l}J_l + N_A\int dE'_\nu\frac{d\sigma_{\nu N,CC}}{dE_l}J_\nu + N_A\int dE'_l\frac{d\sigma_{lN}}{dE_l}J_l \\
&\quad + \frac{m_l}{c\rho\tau_l^d}\int dE'_l\frac{1}{E'_l}\frac{dn_l^d}{dE_l}J_l,
\end{aligned}$$

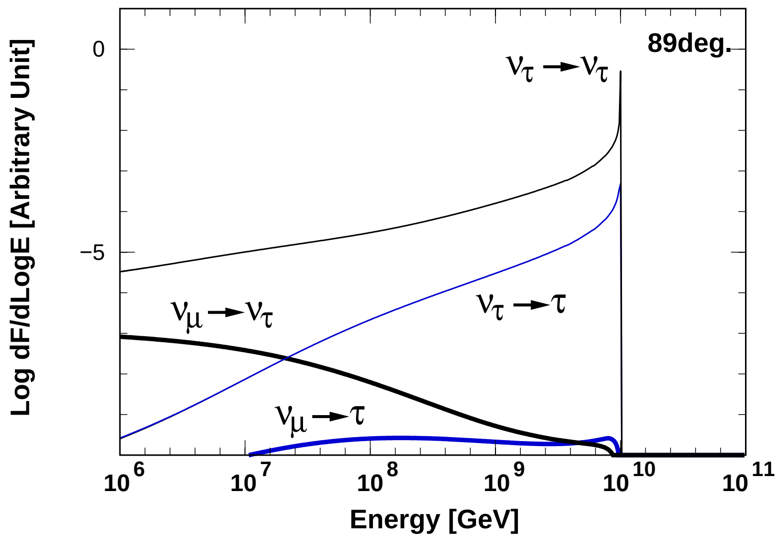

Fig. 1. The energy distributions of ν_τ and τ emerging from the ground for the trajectory with nadir angle of 89 degree which corresponds to path length of 223 km. Primary input spectrum is monochromatic energy distribution of 10^{10} GeV of ν_μ and ν_τ.

where $J_l = dN_l/dE_l$ and $J_\nu = dN_\nu/dE_\nu$ are differential fluxes of charged leptons and neutrinos, respectively, N_A is the Avogadro's number, ρ is the local density of the medium (rock) in the propagation path, σ is the relevant interaction cross sections, dn_l^d/dE is the energy distribution of the decay products which is derived from the decay rate per unit energy, m_l and τ_l^d are mass and the decay life time of the lepton l, respectively. We numerically calculated these equations by building the matrices describing the particle propagation over infinitesimal distance as described in [4-5].

3. Results

Fig.1 shows an example of the energy distribution of propagating particles when spectra of primary EHE neutrinos is monochromatic. The secondary produced neutrinos, muons, and tauons are clearly seen. It should be remarked that ν_τ and τ from primary ν_μ are originated in the heavy lepton production such as $\mu \to \tau^-\tau^+$ which becomes sizable in EHE range. These energy distributions as well as its relative intensities of individual particles give the overall fluxes and the energy spectra of ν, μ, and τ for a given model of EHE neutrino productions.

Fig.2 shows the fluxes of the GZK neutrinos and the secondary produced μ and τ in the earth. We used the primary flux given in [5-6]. The downward going case represents when neutrinos enter into the earth vertically and propagate through 1500 m under the ground. If a neutrino telescope is located at 1500 m below the surface, such neutrinos and leptons blasts an instrumented volume. In

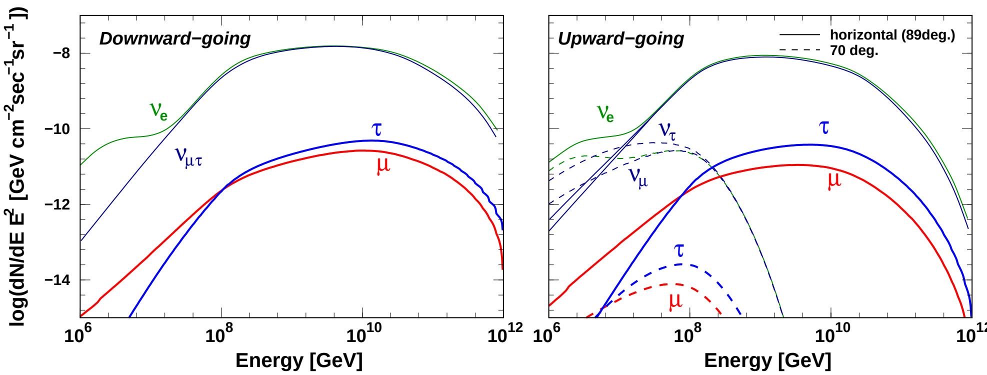

Fig. 2. The intensity of the GZK neutrinos and secondary produced muons and tauons propagating in the earth. Left panel shows the downward going case while the right panel shows the upward going case.

the upward going case the fluxes emerging from the ground strongly depend on nadir angle of the trajectory as the slant depth of propagation path varies significantly depending on the geometry. It is seen that EHE neutrinos are absorbed when nadir angle of trajectory is 70 degree due to the increasing cross sections at EHE.

The secondary produced μ and τ during EHE neutrino propagation in the earth have intensities with ~ 2.5 orders of magnitude lower than neutrinos. μ and even τ in EHE region would not decay but rather interact with nuclei or survive to complete their propagation in the earth. Therefore these EHE μ and τ can be a prime target in EHE neutrino search. Below $\sim 10^8$ GeV, τ becomes more likely to decay and regenerate ν_τ. Consequently the ν_τ flux are higher than the others as clearly seen in the case of the downward going trajectories.

Down-going events are of advantage to detection of EHE neutrino induced μ and τ's due to the wider solid angle factor, if the atmospheric muon background can be completely excluded. Our results indicates $N_{\mu,\tau}(E \geq 0.1EeV) \sim 4 \times 10^{-20}$ cm^{-2} sec^{-1} sr^{-1}, which gives ~ 1 event/year in a km cube scale of neutrino telescope such as IceCube. More study involving the event/background and detector simulation is necessary but the GZK neutrino signature is certainly detectable by a km cube telescope.

4. References

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