

(Ultra-)High Energy Muon Spectrum at Sites of One Cubic Kilometer Detector.

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Abstract. Taking into consideration of the internal structure of the Earth, we calculate neutrino propagation near the one cubic kilometer detector which produce muons via deep inelastic scattering, initiated by mono-energetic neutrino on the surface of the Earth. Their primary energies are 1PeV, 1EeV and 1ZeV.

In the poster session, we give the muon energy spectrum within 60 km together with corresponding neutrino energy spectrum.

Keywords: Muon Propagation, Neutrino Propagation, Fluctuation, Neutrino

I. INTRODUCTION

When we try to detect neutrinos at (ultra-) high energies where their mean free paths are comparable or even shorter than the diameter of the Earth, we must take into consideration of two important factors, namely, the change of the density interior to the Earth[1] and the contribution from neutral current interaction, because the former is directly related to the magnitude of the neutrino cross sections and the latter is related to bigger contribution to the final charged current events from a successive neutral current interaction.

In the present paper, we adopt the preliminary Earth Model[1] as for the density inside the Earth and differential cross section of the neutrinos at (ultra-)high energies obtained by Gandhi *et al.* [2].

In (ultra-) high energies, neutrinos can choose either of following two reactions:

$$\nu_{\mu} + N \longrightarrow \mu + X \quad (1)$$

$$\nu_{\mu} + N \longrightarrow \nu_{\mu} + X \quad (2)$$

First of all, it should be noticed that we detect neutrinos only through the charged particles, namely, muons or electrons and the produced charged particles can be detected only near the detector. Even if (ultra-) high energy charged particles can be produced far from the detector, such charged particles cannot reach the detector. For the moment, we are interested in muons,

because the effective volume for muon detection is far bigger than that for electrons.

We are now interested in the upward neutrinos. Due to the shorten of the mean free paths of the neutrinos as the increase of their energies, generally speaking, frequency of the neutral current events may become bigger than that of the charged current events. Because the charged current interactions at ultra-high energies produce the muons at the location far from the detector and such muons never reach the detector, while the neutral current interactions at ultra-high energies may produce neutrinos whose energies are smaller than that of primary neutrino and the second generation neutrino has longer mean free path compared with that of the first generation as the decrease of energy. Thus, the second generation neutrino may produce the third generation neutrino with longer mean free path via neutral current interaction and so on. In conclusion, the neutral current interaction may have far higher probability to produce muons near the detector in some case, compared with the corresponding charged current interaction. Of course, at the final stage of the interaction, neutrinos produced from the last generation of the neutral current interaction must take part in the charged current interactions which produce finally muon. Otherwise, the original neutral current interactions are never detected.

In the present paper, we give the frequencies of neutral current events which produce finally the muon via charged current interaction at their last stage together with frequencies of the charged current events.

II. THE PROCEDURE FOR OUR MONTE CARLO METHOD

As we must examine the change of the density inside the Earth, we adopt the differential method in the sense of the Monte Carlo methods. We obtain frequency distribution of both charged current events and neutral current events for the incident neutrinos on the surface of the Earth with monochromatic primary energies.

A. The charged current interaction

- (a) We start from an (ultra-)high energy neutrino which is expected to produce muon somewhere in the Earth via charged current interaction.

The probability which occur within in $dx(\rho)$ is given by $dx(\rho)/\lambda_{CC}(E_\nu)$, where $\lambda_{CC}(E_\nu)$ denote a mean free path of the neutrino with the energy E_ν due to charged current interaction. We sample ξ , a random number (0,1). If ξ is smaller than $dx(\rho)/\lambda_{CC}(E_\nu)$, then, we judge the interaction concerned occurs. Next, we sample ξ , random number (0,1) and determine the energy of the muon produced due to charged current interaction, utilizing the following formula.

$$\xi = \frac{\int_{E_{min}}^{E_\mu} D_{CC}(E_\nu, E_\mu) dE_\mu}{\int_{E_{min}}^{E_{max}} D_{CC}(E_\nu, E_\mu) dE_\mu} \quad (3)$$

, where $D_{CC}(E_\nu, E_\mu) dE_\mu$ denotes the charged current differential cross section for deep inelastic scattering.

Thus, the interaction point of the neutrino and the energy of the produced muon are recorded. After that, we sample another neutrino with the same energy and repeat the same procedure until we attain the enough statistics. If ξ larger than $dx(\rho)/\lambda_{CC}(E_\nu)$, then, we judge that the interaction concerned does not occur and we try the same procedure in the previous $dx(\rho)$ to new and next step $dx(\rho)$ and so on.

B. The neutral current interaction

- (b) We start from the neutrino with a given energy whose the mean free path is given by $\lambda_{NC}(E_\nu)$. In the first $dx(\rho)$, we compare ξ , a sampled random number with $dx(\rho)/\lambda_{NC}(E_\nu)$. If ξ is smaller than $dx(\rho)/\lambda_{NC}(E_\nu)$, then, we judge the neutral current interaction occurs within $dx(\rho)$. Next, we determine the produced neutrino energy due to neutral current interaction, utilizing the following equation:

$$\xi = \frac{\int_{E_{min}}^{E_{\nu'}} D_{NC}(E_\nu, E_{\nu'}) dE_{\nu'}}{\int_{E_{min}}^{E_{max}} D_{NC}(E_\nu, E_{\nu'}) dE_{\nu'}} \quad (4)$$

, where $D_{NC}(E_\nu, E_{\nu'}) dE_{\nu'}$ denotes the differential cross section for neutral current.

- (c) The neutrino thus produced has whose energy is $E_{\nu'}$, two choices, namely, one is the charged current interaction and the other is the neutral current interaction. Here we introduce the following quantities:

$$\xi_i = \frac{\sigma_{NC}(E_{\nu'})}{\sigma_{CC}(E_{\nu'}) + \sigma_{NC}(E_{\nu'})} \quad (5)$$

Now, we sample new random number ξ . If $\xi < \xi_i$, then, we judge the neutral current interaction occurs and we go to the procedure (b) with new energy $E_{\nu'}$. Otherwise, we judge the charged current interaction occurs and we go to the procedure (a).

III. FREQUENCY DISTRIBUTION OF CHARGED CURRENT EVENTS AND NEUTRAL CURRENT EVENTS INTERIOR TO THE EARTH

In Figs.1 to 6, frequency distributions of neutrino events with incident energies of 1 ZeV are given for nadir $\cos \theta_\nu$, 1.0, 0.8, 0.6, 0.4, 0.2, 0.0, respectively. The sampling number of the incident neutrinos are 100,000 in every figure. The frequencies are normalized to unity. In Fig.1, we give the frequency distribution of neutrino events with $\cos \theta_\nu = 1.0$. In the figure, CC denote that the frequency of the charged current events (histogram) in which the emitted muon energies are recorded. NC denotes that the frequency of the neutral current initiated events (histograms) which finally produce the muon via the charged current interaction and the energy of the muon concerned are determined. The distance up to the events concerned are measured from the detector which is located at 1.5km below the surface. It is clear from the figure that we could not detect charged current events near the detector at all and only neutral current events can be detected only. The two dumps due to neutral current events which are observed at $\sim 10,000$ km and $\sim 3,000$ km are due to the big change of the density interior to the Earth adopted by the Preliminary Earth Model[1]. The curve in the figure denote the corresponding one to the charged current events which are numerically calculated one. The excellent agreement between histograms and numerical one shows that our Monte Carlo calculation are exactly carried out in the charged current events. In Figs.2 to 6, we give the similar quantities in the cases of $\cos \theta_\nu$, 0.8, 0.6, 0.4, 0.2 and 0.0 (horizontal), respectively. It is clear from these figures that the charged current events cannot be neglected at smaller $\cos \theta_\nu$ (0.2 and 0.0).

In Figs.7 to 12, we give the similar graphs to Figs.1 to 6 for 1 EeV. Except $\cos \theta_\nu = 1.0$, the contribution from charged current interaction is a little larger than that from neutral current contribution. In Fig.13 to 18, we give the similar graphs for 1 PeV. In this energy or more lower energy region, the mean free paths of the neutrino concerned is larger the diameter of the Earth. Therefore, the influence from density interior to the Earth over the frequency are rather small, which shows that their frequency distributions are rather flat.

We are now interested in the detection of the neutrino up to 10^{21} eV. In this case, the maximum muon energy is 10^{21} eV. As the maximum range of 10^{21} eV is ~ 60 km, it is enough for us to search muons which are produced within 60 km from the detector. Finally, we should emphasize the importance of the fluctuation effect in the (ultra-)high energy muon's propagation, because (ultra-)high energy muon has wider range distribution and we understand neutrino energy spectrum can be determined only through the muon behavior.

In the poster session, we give the muon energy spectrum within 60 km together with corresponding neutrino energy spectrum.

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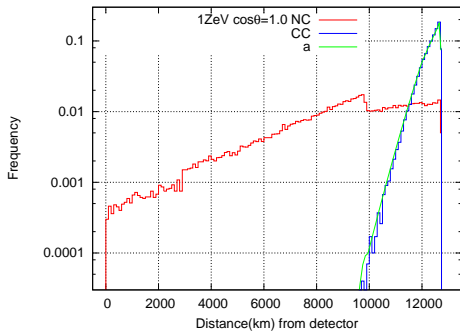


Fig. 1

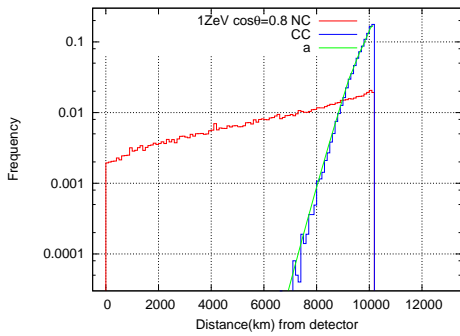


Fig. 2

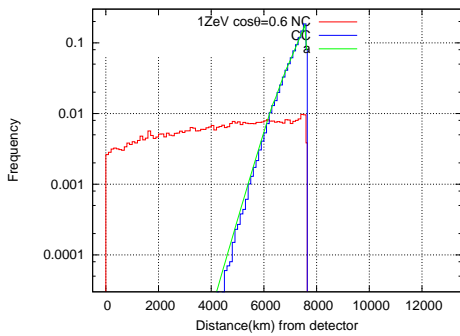


Fig. 3

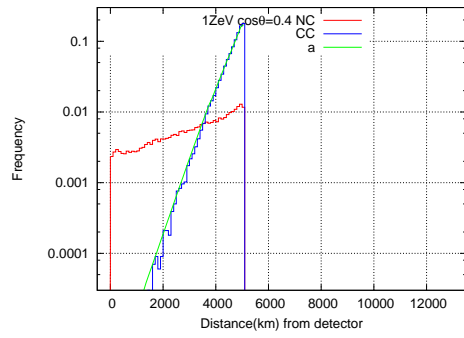


Fig. 4

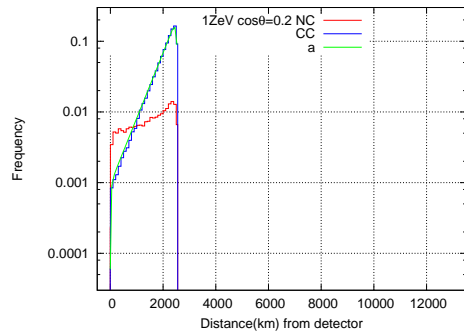


Fig. 5

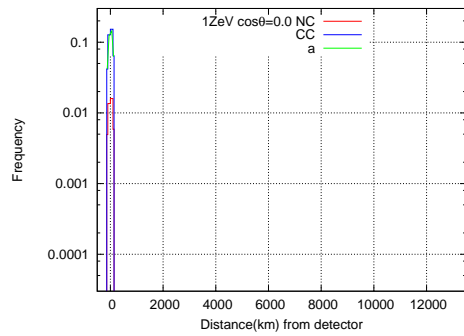


Fig. 6

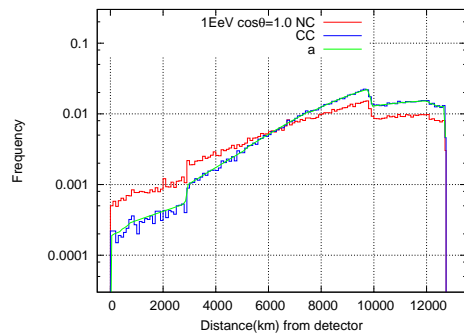


Fig. 7

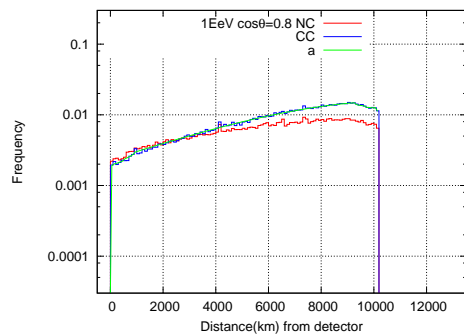


Fig. 8

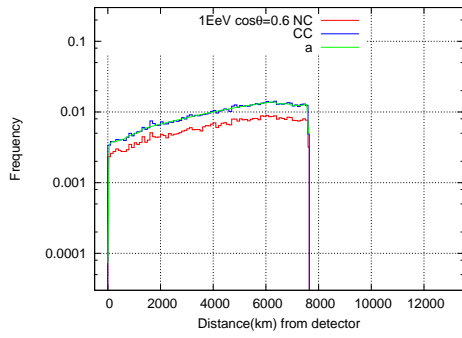


Fig. 9

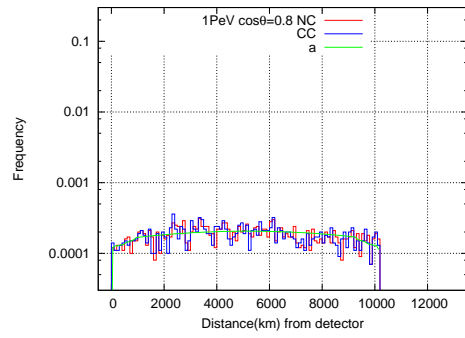


Fig. 14

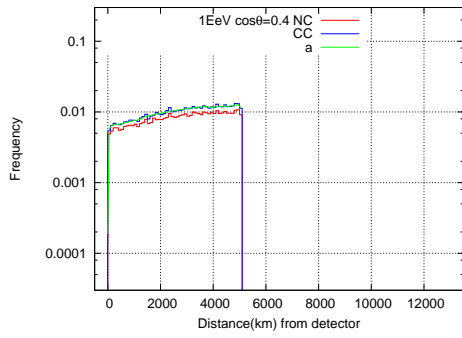


Fig. 10

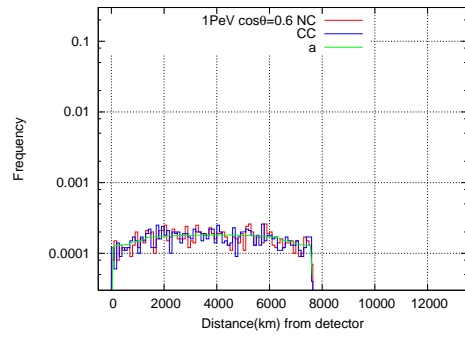


Fig. 15

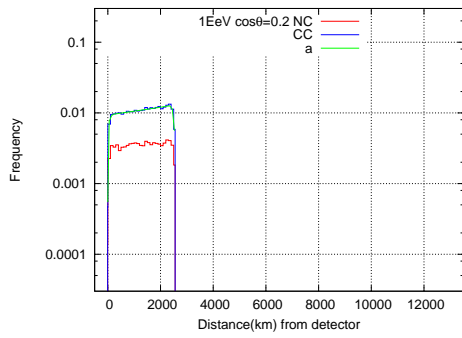


Fig. 11

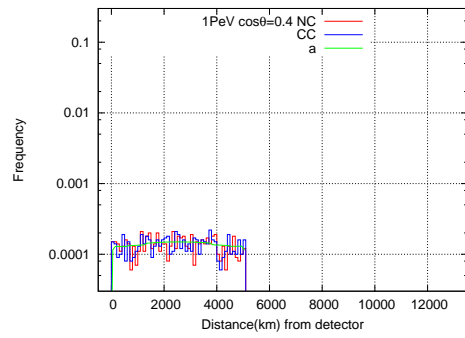


Fig. 16

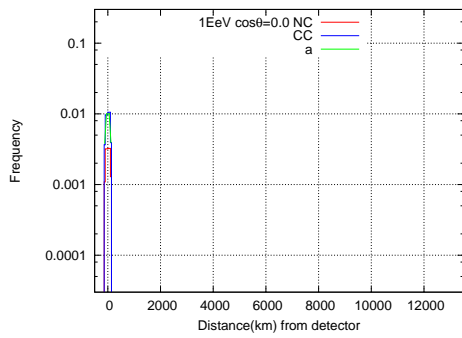


Fig. 12

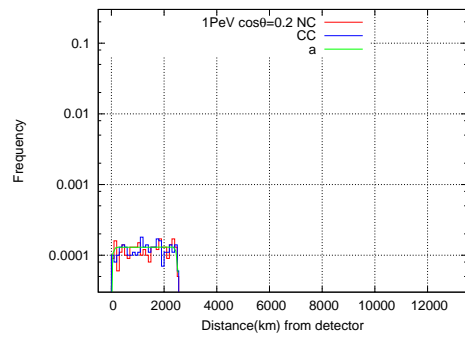


Fig. 17

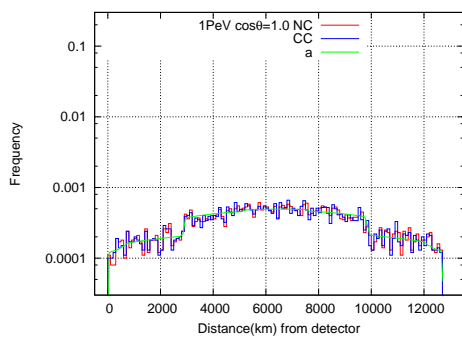


Fig. 13

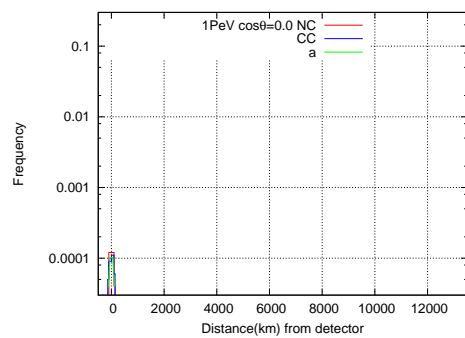


Fig. 18