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Four types of neutrino events produced in the large water tank detector and interrelations among them

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Abstract. The Superkamiokande has been analyzing four different types of neutrino events, namely, [1] fully contained events, [2] partially contained events, [3] stopping muon events, and [4] upgoing through muon events, concluding the existence of neutrino oscillation between muon neutrino and tau neutrino.

Although the results obtained by the Superkamiokande around neutrino oscillation seems to be clear, the logics of their analysis has never been clarified.

We simulate four different types of neutrino events mentoined above in more unified way with more rigourous method in our virtual detector, taking into account stochastic characters of physical processes concerned and clarify interelation among four different types of neutrino events, examining the validity of assertions by the Superkamiokande.

1 Introduction

The Superkamiokande asserts that they have found neutrino oscillation between muon neutrino and tau neutrino, observing significant lack of muon neutrinos from the expected (Kaneyuk, K. 2000, Fukuda, Y. 1998). However, we think that there are many problems to be examined carefully before reaching such definite conclusions. For examples, they neglect uncertainty in the energy determination of neutrino events due to stochastic nature of muons and electron showers and neglect the fluctuation of ranges of muons in their analysis, which may surely influence over the final conclusions around neutrino oscillation problem. Also, they neglect the regeneration effects from the neutral current in neutrino interaction and change of the density effect of the Earth which may be of minor importance compared with former effects.

As we treat neutrinos events which have complicated uncertain factors due to inherent nature of cosmic rays, we should examine them as carefully as possible and analyze them as rigorously as possible before reaching such definite conclusions.

In the Superkamiokande, they analyze four different types of neutrino events, namely, [1] fully contained events ,[2] partially contained events,[3] stopped muons events, and [4] upgoing through muons events, and have obtained the same conclusion, namely the confirmation of the existence of the neutrino oscillation. In our opinion, four different types of the neutrino events belong to different categories each other from the point of uncertainties of the qualities of experimental data, they should be treated in more carefully with unified treatment.

In this paper, we simulate neutrino events inside and outside the water tank detector as same as the Superkamiokande, starting from the incident neutrino energy spectrum at the opposite side of the Earth to us. Simulated events thus obtained are compared with experimental data obtained by the Superkamiokande
(Kaneyuki,K 2000, Fukuda,Y 1998).

2 Algorithm for our simulation

We define $P_{sur}(E_\nu, t, \cos\theta)$, the survival probability at the depth t from the detector underground for incident neutrino with energy E_ν for zenith angle θ and, $P_{int}(E_\nu, t, \cos\theta)\,dt$, neutrino interaction probability for the same condition as follows:

$$\begin{aligned} &P_{sur}(E_\nu, t, \cos\theta) \\ &\quad = \left(1 - \frac{dt}{\lambda_1(E_\nu, t_1, \rho_1)}\right) \times \left(1 - \frac{dt}{\lambda_2(E_\nu, t_2, \rho_2)}\right) \times \\ &\qquad \times \ldots \times \left(1 - \frac{dt}{\lambda_n(E_\nu, t_n, \rho_n)}\right) \end{aligned} \quad (1)$$

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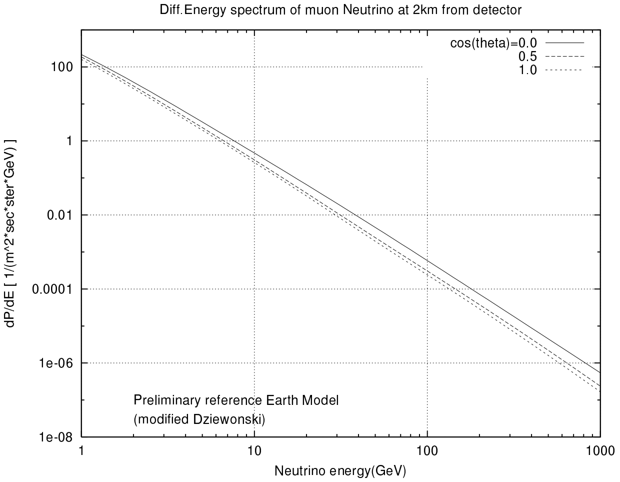

Fig. 1. The survival muon neutrino energy spectrum at $2km$ from the detector underground located at $1.5km$ from the surface of the Earth.

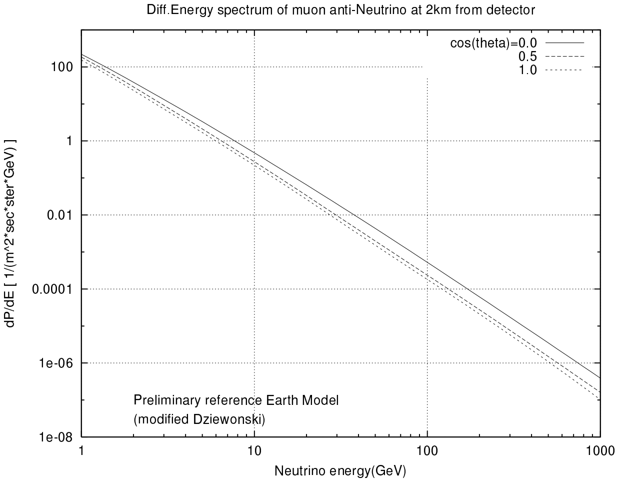

Fig. 2. The survival anti-muon neutrino energy spectrum. The situation is the same in Fig.1.

$$
\begin{aligned}
&P_{int}(E_\nu, t, \cos\theta)\,dt \\
&=\left(1-\frac{dt}{\lambda_1(E_\nu, t_1, \rho_1)}\right)\times\left(1-\frac{dt}{\lambda_2(E_\nu, t_2, \rho_2)}\right)\times\ldots\times \\
&\times\left(1-\frac{dt}{\lambda_{n-1}(E_\nu, t_{n-1}, \rho_{n-1})}\right)\times\left(\frac{dt}{\lambda_n(E_\nu, t_n, \rho_n)}\right) \quad (2)
\end{aligned}
$$

, where we utilize the mean free paths of neutrinos(Gandhi et al.1996,1998) and the Preliminary Earth Model for density profile(Dzewonski 1989).

By combining (1) and (2) with the incident neutrino energy spectrum at the opposite side of the Earth (Honda et al.1995), we obtain $N_{sur}(E_\nu, t, \cos\theta)$, survival neutrino energy spectrum at the depth t and $N_{int}(E_\nu, t, \cos\theta)\,dt$ in the following,

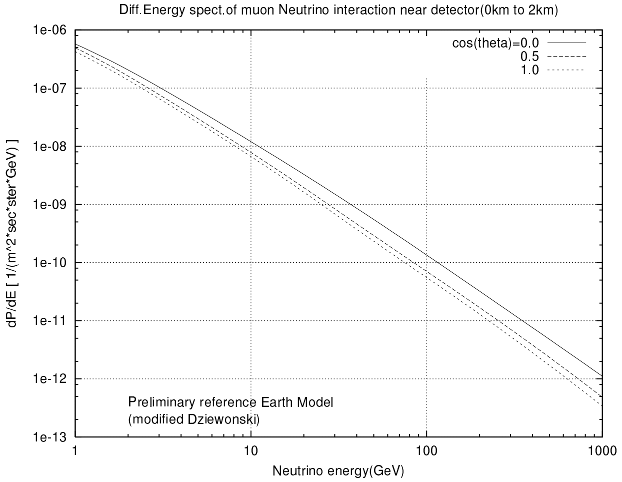

Fig. 3. The interaction muon neutrino energy spectrum produced between the surface of the detector undergroung and $2km$ toward the center of the Earth. The detector is located at $1.5km$ from the surfaceof the Earth.

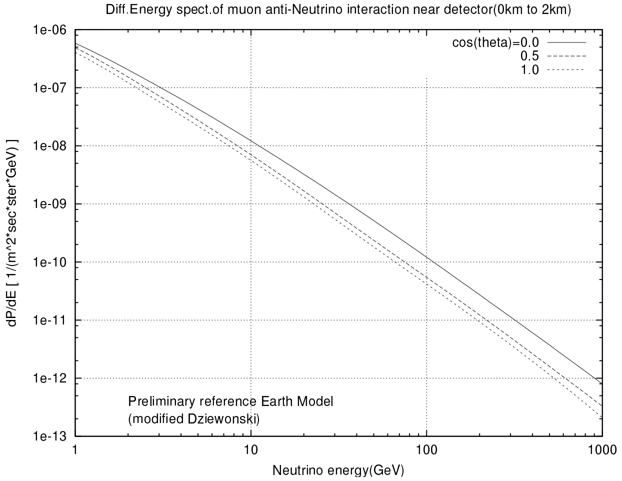

Fig. 4. The interaction anti-muon neutrino energy spectrum. The situation is the same as Fig.3.

$$
\begin{aligned}
&N_{sur}(E_\nu, t, \cos\theta) \\
&\quad = \quad N_{sp}(E_\nu, \cos\theta)\times P_{sur}(E_\nu, t, \cos\theta) \qquad (3)
\end{aligned}
$$

$$
\begin{aligned}
&N_{int}(E_\nu, t, \cos\theta)\,dt \\
&\quad = \quad N_{sp}(E_\nu, \cos\theta)\times P_{int}(E_\nu, t, \cos\theta)\,dt \qquad (4)
\end{aligned}
$$

,where $N_{sp}(E_\nu, \cos\theta)$ denotes incident neutrino energy spectrum on the surface of the Earth(Honda et al.1995).

We give survival muon neutrino energy spectrum in Fig.1 and anti-muon neutrino energy spectrum in Fig.2 by using incident neutrino spectrum by Honda et al.1995.

We give the interaction muon neutrino energy spectrum in Fig.3 and the interaction anti-muon energy spectrum in Fig.4.

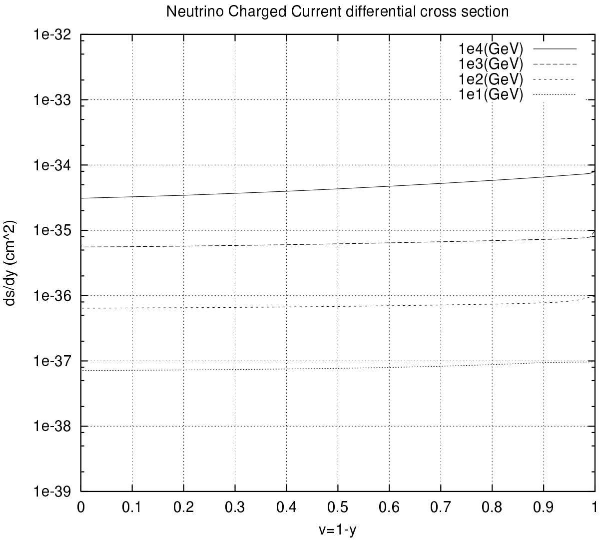

Fig. 5. Differential cross section for charged current neutrino interaction from Gandhi et al. The v denotes the ratio of transferred muon energy to incident neutrino energy.

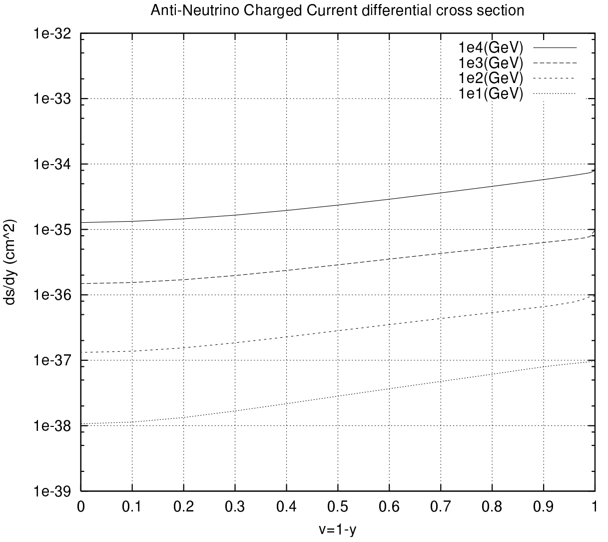

Fig. 6. Differential cross section for charged current anti-neutrino interaction from Gandhi et al.

by using the mean free path of neutrino interaction (Gandhi et al.1996,1998).

We simulate E_ν, the neutrino energy which join in the reaction, by using the interaction neutrino energy spectrum and ξ, uniform randum number between 0.0 and 1.0 in the following.

$$\xi = \frac{\int_{E_{min}}^{E_\nu} N_{int}(E_\nu, t, \cos\theta)\, dE_\nu}{\int_{E_{min}}^{E_{max}} N_{int}(E_\nu, t, \cos\theta)\, dE_\nu} \qquad (5)$$

Next, we simulate E_μ, the energy of (anti-)muon produced in the charged current interaction. Differential cross section for charged current interaction are given in Gandhi et al.1996,1998 and Reno,M.H 1999, examples of which are shown in Fig.5 and Fig.6. The energy of the muon produced in the charged current interaction is simulated in the following way,

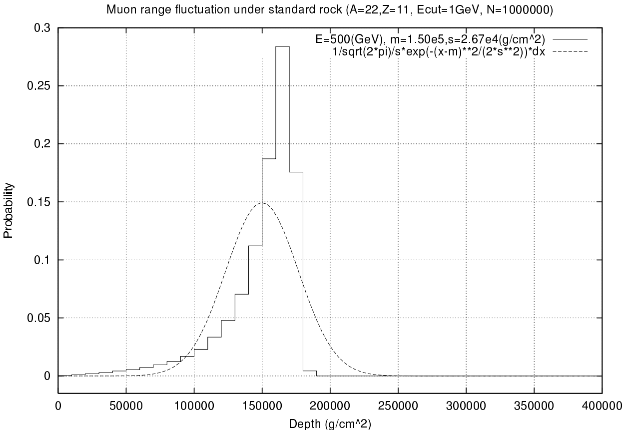

Fig. 7. Distribution of range fluctuation of the muon with $500 GeV$ in the standard rock.

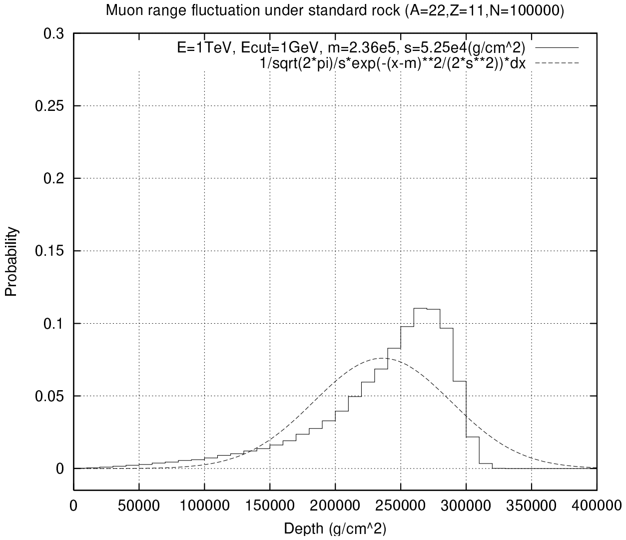

Fig. 8. Distribution of range fluctuation of the muon with $1 TeV$ in the standard rock.

$$\xi = \frac{\int_{E_{min}}^{E_\mu} D(E_\nu, E_\mu)\, dE_\mu}{\int_{E_{min}}^{E_{max}} D(E_\nu, E_\mu)\, dE_\mu} \qquad (6)$$

,where $D(E_\nu, E_\mu)\, dE_\mu$ is given in Gandhi et al.1996, 1998 and Reno,M.H 1999.

3 Fully contained events and partially contained events

By the definition that the event should be occurred inside the detector, we should simulate the interaction point, t, in such way that t is satisfied with the following equation (7)

$$\xi = \frac{\int_0^t P(t, \lambda(E_\nu, t))\, dt}{\int_0^T P(t, \lambda(E_\nu, t))\, dt} \tag{7}$$

,where $P(t, \lambda(E_\nu, t))$ is the distribution function for free path of the charged current neutrino interactions.
$P(t, \lambda(E_\nu, t))$ is given as

$$P(t, \lambda(E_\nu, t))\, dt = \frac{1}{\lambda(E_\nu, t)} exp\left(-\frac{t}{\lambda(E_\nu, t)}\right)\, dt \tag{8}$$

,where $\lambda(E_\nu, t)$ denote mean free path of neutrino with E_ν for neutrino interaction, and T is the possibe maximum distance along which the interaction is ocurred. The interaction point,t, is measured from the entrance point of the incident neutrino into the detector.

As the mean free path of neutrino interaction is too large compared with T, then, we obtain the interaction point of the neutrino event concerned as,

$$t = \xi \times T \tag{9}$$

from (7).

By using (5),(6) and (9), we simulate the neutrino event inside the detector.

If the energy of the muon thus produced at the point t in the detector is greater than minimum energy for ionization loss, then it is identified as the fully contained event, otherwise, the partially contained event

4 The upward going muon and the stopping muon

These muons are generated outside the detector and consequently penetrate into the detector from outside. If the energy of the entering muon is greater than minimum energy for passing through the detector, such neutrino event is identified as the upward going on, otherwise, it is identified as the stopping muon.

The energies of muon thus produced in charged current interactions outside the detector may be enough high to be influenced by the processes of bremsstrahlung, pair production and nuclear interaction. The ranges of such muons are fluctuated due to stochastic characters of these processes, which are one of main sources for uncertainty on the informations of physical events concerned. Some examples of the range fluctuation of high energy muons are given in Fig.7 and Fig.8.

Consequently, either upgoing through muon or the stoppimg muon are much fluctuated, even compared with the partially contained events. In this paper, we examine qualities of both experimental data and the method for the analysis in physical events which belong to different categories, and discuss interrelations among them in the Superkamiokande in our unified scheme.

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