Examination on SK atmospheric neutrino experiment by the computer experiment

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Abstract. We examine neutrino events occurring inside the SuperKamiokande (SK) detector and those occurring outside the same detector using computer simulations. We analyze the zenith angle distribution of Fully Contained Events and show the method for the determination of the incident neutrino by the SK group is unreliable. The analysis of the neutrino events occurring outside the detector shows these events agree with the Monte Carlo simulation without oscillation.

In our oral presentation at TAUP2005, we examined various topics in atmospheric neutrinos in the SK and K2K experiments. However, in this short paper, we are obliged to present our conclusions without detailed derivations and verifications due to the restrictions on paper length. We must omit consideration of the K2K experiment here for the same reason. Readers are requested to refer to our (forthcoming) papers [1] for detailed examinations.

SK deals with the neutrino events occurring inside the detector (Fully Contained Events and Partially Contained Events) and events occurring outside the detector (Upward Through-Going Muon Events and Stopping Muon Events). In the analysis of the Fully Contained Events and Partially Contained Events, the SK group adopts the assumption that the direction of the incident neutrino is the same as that of the emitted lepton. In order to avoid any misunderstanding, we reproduce this assumption from the original SK papers:

[a] “However, the direction of the neutrino must be estimated from the reconstructed direction of the product of the neutrino interaction. In water Cherenkov detectors, the direction of an observed charged lepton is assumed to be the direction of the neutrino.” [2]

[b] “The direction of neutrino for FC single-ring sample is simply assumed to be the same as the reconstructed direction of muon. Zenith angle of neutrino is reconstructed as follows: \( \cos \theta_{\nu}^{rec} = \cos \theta_{\mu} (8.17) \) where \( \cos \theta_{\mu} \) and \( \cos \theta_{\nu}^{rec} \) are cosine of the reconstructed zenith angle of muon and neutrino, respectively.” [3]

In the analysis of neutrino events occurring inside the detector, quasi elastic scattering (QEL) is the most important process, because QEL produces a single ring event in Fully Contained
Events which result in the most clear cut events for analysis. Here, we examine the influence of neglecting the scattering angle of the charged lepton due to QEL over the final zenith angle of the charged lepton. Let $\theta_s$ and $\varphi_s$ be the scattering angle and the azimuthal angle, respectively. In the SK analysis, the zenith angle of the particles concerned are utilized. Here, let $(\ell, m, n (= \cos \theta))$ and $(\ell_{\mu}, m_{\mu}, n_{\mu} (= \cos \theta_{\mu}))$ be the direct cosine of the incident neutrino and that of the emitted muon, respectively. In this case, the relation between $(\ell, m, n)$ and $(\ell_{\mu}, m_{\mu}, n_{\mu})$ is given as follows:

$$
\begin{pmatrix}
\ell_{\mu} \\
m_{\mu} \\
n_{\mu}
\end{pmatrix}
=\begin{pmatrix}
\cos \theta \cos \varphi & -\sin \varphi & \ell \\
\cos \theta \sin \varphi & \cos \varphi & m \\
-\sin \theta & 0 & n
\end{pmatrix}
\begin{pmatrix}
\sin \theta_s \cos \varphi_s \\
\sin \theta_s \sin \varphi_s \\
\cos \theta_s
\end{pmatrix}
$$

where $\cos \theta_{\nu}$ and $\cos \theta_{\mu}$ denote the zenith angle of the incident neutrino and that of the emitted muon, respectively. Here, $\ell = \sin \theta \cos \varphi$ and $m = \sin \theta \sin \varphi$.

It should be noticed that the influence of the azimuthal angle of the events over their zenith angle can be very significant, particularly for inclined neutrinos and furthermore, the azimuthal angle may play an important role in the “transmutation” between Fully Contained Events and Partially Contained Events in real analysis.

We obtained the zenith angle of the emitted muon for each sampled incident neutrino as a function of zenith angle and energy. In Figure 1, we give the scatter plot between $\cos \theta_{\nu}$ and $\cos \theta_{\mu}$. The SK group utilize the relation (8.17) given above. It is, however, clear from Figure 1 that such an assumption holds above 5 GeV at most and that it does not hold at lower energies, where most neutrino events of interest exist.

![Figure 1](image1.png)  
**Figure 1.** Correlation between $\cos \theta_{\nu}$ and $\cos \theta_{\mu}$ for different neutrino energy ranges.  

![Figure 2](image2.png)  
**Figure 2.** The relation between the zenith angle distribution of the incident neutrinos and corresponding one of the emitted muons.  

For the zenith angle distribution of upward neutrinos whose energy spectrum in the SK detector is derived from the incident neutrino energy spectrum at the surface of the Earth, we could calculate the corresponding distribution of the emitted muons following Eq.(1). In this case, we simulate the azimuthal angle as well as the scattering angle of the emitted leptons exactly following the probability function due to QEL. In Figure 2, the zenith angle distribution of the emitted muons is given together with the corresponding parent incident neutrinos. According to the SK assumption, the zenith angle distribution of the emitted muons is the same as the distribution of the incident neutrinos. As illustrated, however, the muon distribution is quite different from that of the incident neutrinos. This is the reason why the determination of the incident neutrino direction by the SK group is not reliable. Namely, we can not neglect the effect of the scattering angle due to QEL in the analysis of events occurring...
inside the detector. Also, we can not neglect the effect of the azimuthal angle in the analysis. The SK group do not treat the effect of the azimuthal angle in their analysis.

The SK group assert that they have found the signature of neutrino oscillations in their analysis of Fully Contained Events and Partially Contained Events [4]. It is, however, necessary to analyze Fully Contained Events separately from Partially Contained Events.

In Figure 3, we give the L/E distribution due to QEL in the presence of oscillations with the SK parameters. In our case we exactly simulate neutrino events, taking into consideration the effects of both back-scattering and azimuthal angle, while in the SK case we adopt the SK group’s assumption that the incident neutrino and emitted muon have the same direction. In both our case and the SK case, we analyze Fully Contained Events exclusively to eliminate ambiguities as much as possible, whereas the real analysis by the SK group is done using a mixture of Fully Contained Events and Partially Contained Events. In our case, we can clearly see a dip around (301–501) km/GeV, which roughly coincides with the theoretically expected 530 km/GeV. In the SK case, the corresponding dip occurs at (50.1–63.1) km/GeV, which is smaller than 530 km/GeV by one order of magnitude. This also shows that the SK group’s assumption is not reliable.

In contrast to the analysis of neutrino events occurring inside the detector, we can assume the direction of the emitted lepton is the same as that of the incident neutrino in the analysis of neutrino events outside the detector, namely, Upward Through-Going Particles Events and Stopping Particles Events may be generated exclusively by high energy muons due to deep inelastic scattering, where their scattering angles could be neglected. We analyze physical events, taking into account the effect of the range fluctuation exactly, while SK use the average range of the muon concerned, being helped by an “observation probability”. This does not reflect the real situation of limited statistics. In Figures 4 and 5, we give the zenith angle distributions of Upward Through-Going Muon Events and Stoping Muon Events, taking into account all fluctuation effects exactly, and compare our results with the experimental data by SK directly. The SK experimental data are consistent with our results without oscillation [5].

Thus, we find the analysis of atmospheric neutrinos by the SK group does not provide definite evidence for the existence of the neutrino oscillations.

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