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An Analysis of the Muon-Like Events as the Fully Contained Events in the Super-Kamiokande through the Computer Numerical Experiment

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Abstract: We analyze the muon-like Events(single ring image) in the Super-Kamiokande (SK) detector by the Computer Numerical Experiment. Assuming the parameters of the neutrino oscillation obtained by the SK which characterize the type of the neutrino oscillation, we reproduce the zenith angle distributions of the muon-like events in Fully Contained Events and compare them with the distributions obtained by the SK. Also, we carry out the L/E analysis of the muon-like events by the Computer Numerical Experiment and compare them with those by the SK.

Introduction

In Super-Kamiokande collaboration – hereafter, SK, simply –, they assume that the direction of the incident neutrino is as same as the direction of the emitted lepton [1], [2]. Hereafter, we call this assumption as *the SK assumption on the direction*. In an another paper (abstractID:251), we show that SK do not determine the direction of the incident reliably [3]. In the present paper, we compare our distributions of the neutrino events under the SK neutrino oscillation parameter ($\sin^2 2\theta = 1.00$ and $\Delta m^2 = 2.1 \times 10^{-3}\mathrm{eV}^2$) in the case that the scattering angle of the lepton in quasi elastic scattering(QEL)[4] are correctly taken into account with the actual SK distributions and examine the validity on the neutrino oscillation parameters determined by the SK collaboration.

We perform the Computer Numerical Experiment for live days which is exactly as same as that of 1489.2 days by SK.

Correct distributions from the computer numerical experiment

In the another paper[3], we show that the relation between $\cos\theta_\nu$, cosine of the zenith angles of the incident neutrinos and $\cos\theta_\mu$, the zenith angles of the emitted leptons for the upward incident neutrino energy spectrum (no oscillation) near SK detector. In this case, we examine the relation between $\cos\theta_\nu$ and $\cos\theta_\mu$ exclusively from the view point of the kinematics, without considering the actual condition around the detector.

Correlation diagram between $\cos\theta_\nu$ and $\cos\theta_\mu$

In obtaining Figure 1 and Figure 2, we consider the following conditions: [A] The generated neutrino events in the detector are judged, which are classified as either *Fully Contained Events* or *Partially Contained Events*. Finally, *Fully Contained Events* are selected. [B] We consider both the neutrino interaction energy spectra from the upward

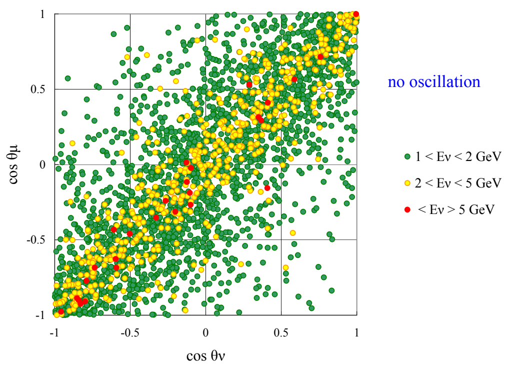

Figure 1: Correlation diagram between $\cos\theta_{\nu(\bar{\nu})}$ and $\cos\theta_{\mu(\bar{\mu})}$ for *Fully Contained Events* in the case without neutrino oscillation).

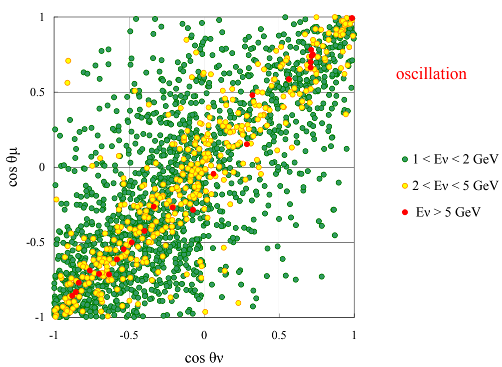

Figure 2: Correlation diagram between $\cos\theta_{\nu(\bar{\nu})}$ and $\cos\theta_{\mu(\bar{\mu})}$ for *Fully Contained Events* in the case with neutrino oscillation(SK neutrino oscillation parameter)).

and downward. In Figure 1, the relation between $\cos\theta_{\nu+\bar{\nu}}$ and $\cos\theta_{\mu+\bar{\mu}}$ are given for no oscillation, in which the neutrino interaction energy spectrum with no oscillation is utilized. In Figure 2, the similar relation are given in the presence with neutrino oscillation, in which the corresponding spectrum with SK neutrino oscillation parameters is utilized. Both Figure 1 and Figure 2 show clearly that SK assumption on the direction, $\cos\theta_{\nu(\bar{\nu})} = \cos\theta_{\mu(\bar{\mu})}$, does not hold in both cases with and without neutrino oscillation, even if statistically, because it comes from the property of the kinematics in the neutrino interactions, which is universal, irrespective of oscillation or no oscillation. The correlation between $\cos\theta_{\nu+\bar{\nu}}$ and $\cos\theta_{\mu+\bar{\mu}}$ in the second quadrant in both Figure 1 and Figure 2 means the relation downward neutrino and upward leptons and corresponding ones in the forth quadrant the relation between upward neutrinos and downward leptons. It is clear from these phenomena in the second and the fourth quadrants that we could not neglect the backscattering effect due to QEL for *Fully Contained Events* for muon. The first quadrant in Figure 1 and Figure 2 denote the relation between upward neutrinos and upward leptons, while the third quadrant denote the relation between downward neutrinos and downward leptons. Comparing the first quadrant in Figure 1 with the corresponding one in Figure 2, it is clear that events number in Figure 2 is smaller than that in Figure 1 due to the neutrino oscillation.

The relation between incident neutrinos and the emitted leptons

In Figure 3, we give the zenith angle distributions for the upward neutrinos (ν and $\bar{\nu}$) and the emitted muons (μ and $\bar{\mu}$) by these neutrinos. The strong irregularity in the upward neutrinos denotes that the statistics by which we could draw definite conclusions is not enough, reflecting the complicated neutrino interaction energy spectrum concerned due to the SK neutrino oscillation parameters. Also, the existence of the backscattered muon could not be neglected. In Figure 4, we compare the zenith angle distribution for the emitted muons without oscillation with the corresponding ones with oscillation in the absolute values by our Computer Numerical Experiment. In the zenith angle region, including the contribution from both upward and downward neutrinos.

The number of the upward muons with oscillation is significantly smaller than that without oscillation, as they must be. Neutrino events with oscillation are surely smaller than those without oscillation. However, real situation is pretty complicated. Upward neutrinos produce the backscattered muons which leak out from the region $\cos\theta_\mu = 0 \sim 1$, while downward neutrinos produce the backward muon which penetrate into the same region. As the flux of the upward neutrinos are smaller than these of downward neutrino, the difference of the neutrino events between the case with oscillation and the case without oscillation are smaller in our case than in SK case. Namely, the neutrino oscillation is exaggerated in SK case than in the real one. In Figure 5, we compare our case with oscillation, our case without oscillation and SK experimental data. Comparison of our data with SK data in the same live days tells us that the fluctuation in both our case with oscillation and our case without oscillation are rather big, which denotes we have not enough statistics for drawing definite conclusion. Particularly strong irregularity in the downward neutrino region shows the direct reflection from the complex structure of the upward neutrino energy spectrum with oscillation. The comparison of our data with SK with oscillation tell us that the possibility that SK data agree with the data without oscillation is could not be rejected.

Comparison of L/E analysis by Computer Numerical Experiment with that by SK

Accuracy in the determination for the direction of the incident neutrino is strongly connected with L, the distance between the SK detector and the surface of the Earth at which the neutrino concerned is produced. Therefore, the L/E analysis may offer a mean for verification on the excellent determination for the direction of the incident neutrino.

In Figure 6, we give the events number as a function of L/E in the case of the no oscillation. Downward neutrinos contribute to the first "mountain", while upward neutrinos contribute to the second "mountain". Both the downward neutrinos and upward neutrinos with near horizontal direction contribute to the "dip". The existence of the dip coming from L/E analysis is independent on the existence of neutrino oscillation.

Now, let us consider upward neutrino events only. In Figure 7, we give the neutrino events due to upward neutrinos (Our case). As we show in Figure 3, we could not neglect the effect of the backscattering. If we consider the events with backscattering, SK estimates the direction of the leptons with back scattering as the original direction of the incident neutrino. In this case, SK should have such L/E distribution in the figure (SK case). It is clear that [Our Case] is quite differ-

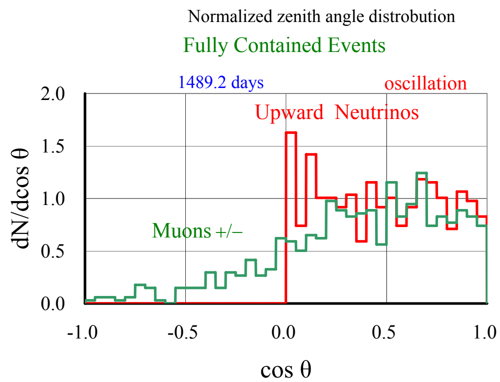

Figure 3: The zenith angle distribution for the upward incident neutrinos and their emitted muons.

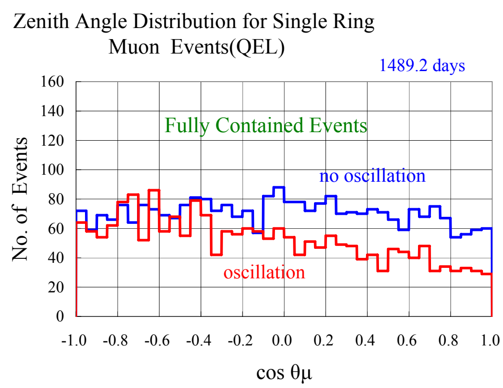

Figure 4: The zenith angle distribution for the emitted muon in the neutrino events both with neutrino oscillation and without oscillation.

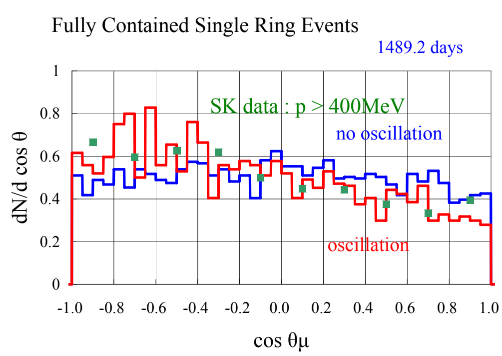

Figure 5: The normalized zenith angle distribution for the emitted muon in the neutrino events both with neutrino oscillation and without oscillation and the comparison with the corresponding SK data.

ent from [SK case]. In Figure 8, we compare our L/E distribution with that by SK after normalization. Original SK data is taken from Ashie et.al.[5]. It should be noticed from the figure that the shape of the distribution in our results is quite different from that by SK. In our opinion, the reasons why both results disagree is as follows. One reason is that SK do not measure L correctly, because of *the SK assumption on the direction* and the second is that SK include the Partially Contained Events. By its definition, SK could not measure the energy E. Also, it should be noticed that our dip exactly appear in the predicted region(L/E∼500km/GeV). It verifies our computer numerical experiment is performed in a correct way.

Conclusion

It is desirable that the zenith angle distribution of single ring muon event as *Fully Contained Events* and L/E distribution by these same events in SK are carefully re-examined.

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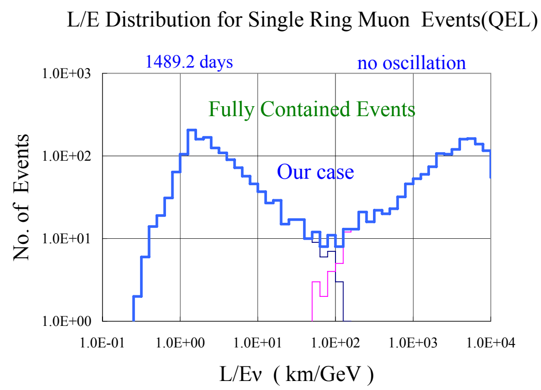

Figure 6: L/E distribution for single ring muon events without neutrino oscillation.

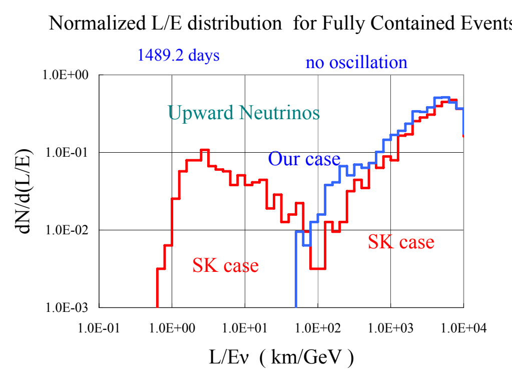

Figure 7: L/E distribution for *Fully Contained Events* from upward neutrino.

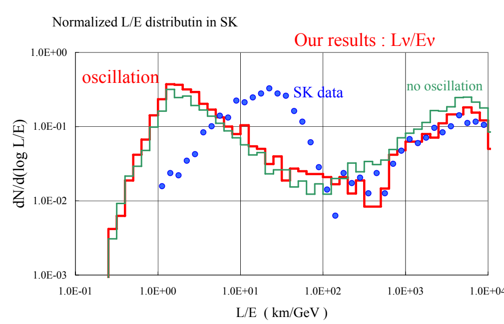

Figure 8: Normalized L/E distribution for single ring muon events.