Calculation of Atmospheric Neutrino and the Sensitivity of Angular Dependences to Various Models.

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Abstract

The recent discovery of neutrino mass by SuperKamiokande (Fukuda et al., 1998) has made it crucial to calculate the atmospheric neutrino accurately. However, there are large uncertainties yet in the basic model of the calculation, such as primary cosmic ray flux and hadronic interaction. They still remeain as the main sources of the uncertainty in the calculation of atmospheric neutrino. We study of the sensitivity of the atmospheric neutrino to those uncertainties, focusing on the angular dependence. It is found that the shape of angluar dependence of the atmospheric neutrino alsmost stay the same, while the primary cosmic ray, hadronic interaction, and atmospheric models vary in a wide parameter range. The vertical/horizontal flux ratio varies less than 5 % for muon neutirno below 30 GeV and 10 % for electron neutrino below 10 GeV. This stability of angular dependences neutrino will be useful to study of the neutrino masses and mixing angles.

1 Introduction:

The recent observation of atmospheric neutrinos by SuperKamiokande has made us convinced of the existence of neutrino oscillation and the nonzero neutrino masses. Now the major interest has been shifted from the proof of neutrino oscillations to the determination of the neturino mass and mixing angles accurately. For this purpose, some accelerator experiments are being carried out. However, it is stressed that the atmospheric neutirno is still a powerful tool to study the neutrino physics, if we can predict the flux accurately.

The souce of uncertainty of in the calculation of atmospheric neutrino is in the primary cosmic ray model and in the hadronic interaction model. The measured primary cosmic ray flux has a large variation in the absolute values. Also there have been many experimental study of the hadronic interaction but most of them are not useful for the calculation of atmospheric neutirno. Therefore, we have to assume that there are still uncertainties in these basic quantities.

In this paper we mainly study the effect of these uncertainty on the angular dependence of the atmospheric neutrino flux. since it is often used to study the neutrino oscillation parameters, espcially, the mass difference. A similar study was done for the flux ratio of atmospheric neutrinos (Honda, M., 1998), and was found to be very small but very different from the observed ratio. This fact is considered as a strong evidence for the neutrino oscillations.

2 Primary Cosmic Ray Models

The primary cosmic ray proton flux observed by recent experiments are clearly lower then the flux model used by Honda et al., 1995 (HKKM) in the energy reagion of 10 GeV – 100 GeV. These flux observed by the "new generation" experiments seem to agree each other, but, the proton flux > 100 GeV is still very uncertan. We take 3 model for the calculation: high, mid, and low primary flux models as are shown in Fig. 1, the high flux model is the model used by HKKM.

3 Interaction Model

HKHM used NUCRIN for E < 5 GeV, LUND(Jetset 6.3) for 5 GeV < E < 500 GeV, and Cosmos

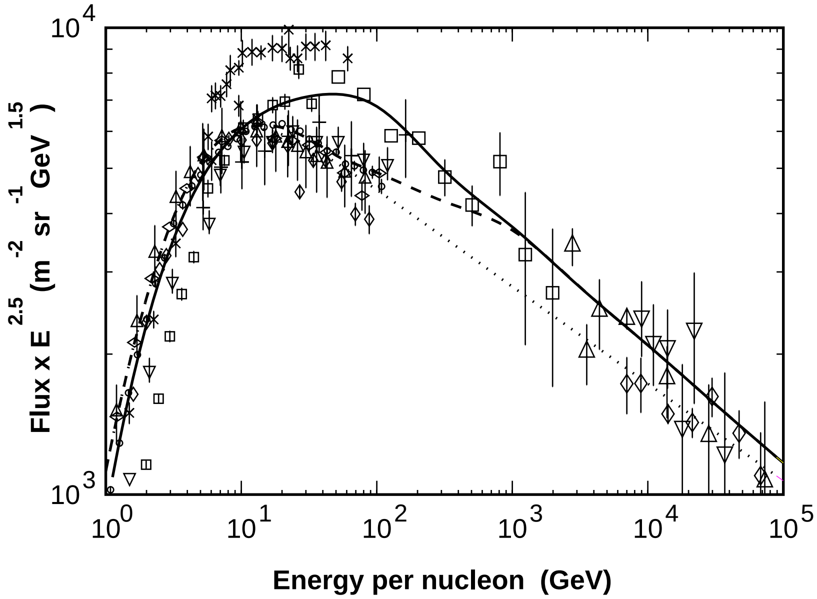

Figure 1: Observed cosmic ray proton flux with model for calculation. Crosses from Webber et al. 1979, open upward triangles stand for Seo, W.S., et al., 1993 open squares for Pappini, P., et al., 1993, open downward triangles for Menn, W., et al., 1997, open vertical diamonds for Barliellini, G., et al., 1997, and open horizontal diamonds for Orito. S., 1998. pluses, closed squares, closed vertical diamond, closed upward triangles, and closed downward triangles are from Refs[22],[26],[25],[34],[35],[36], and [38] of Honda et al., 1995. respectively.

ad hoc model for E > 500 GeV. It has been pointed that this conbination has a discontinuity at 5 GeV for pion multiplicity.

Starting from the combinarion of these interaction models, some improvements are made to the hadronic interaction code so that the secondary particle spectram can be modified without violating the conservation lows.

Here we consider the energy distribution of incident particle energy to the secondary particles by two way: by the change of multiplicity of the particle and by the change of energy spectrum of secondary particel without changing the multiplicity. In the Fig. 2, are shown the examples of a variation of interaction model which change the energy distribution to pions by ± 20 %, with the experimental data from Eichten, T., et al., 1972. A similar variation is also considered for the kaons. To retain the energy eonservation, the secondary particle energy spectrum of nucleons are modified to conpensate the change caused by the change of second particle energy spectrum and multiplicity of pions and kaons.

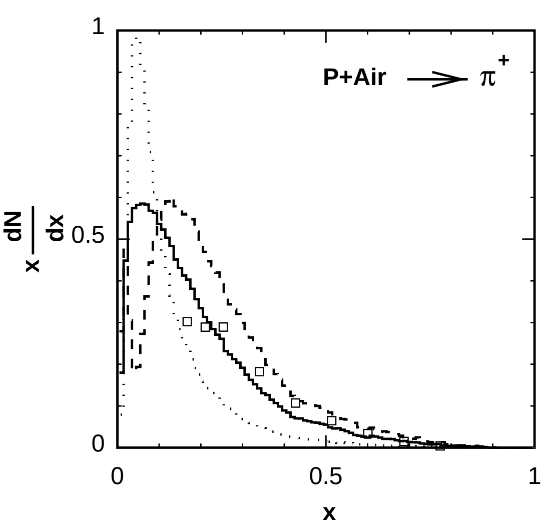

Figure 2: Example of modification of interaction model for secondary particle energy spectrum with experimental data from Eichten, T., et al., 1972.

We consider here the change of energy distribution of 20 % for each method both for pions and kaons.

4 Atmospheric Structure

The US-standard-model is widely used as the atmospheric structure model in the Monte Carlo simulation of cosmic ray propagation in the atmosphere. However, it is noted that this model is for the average feature of atmosphere. The atmosphere is known to have different structure for the position with different lattitudes and different seasons of a year. Therefore, the actual density structure may differ from the model for a particular site and time.

In Fig.3, is shown the comparison of measured pressure and that of US-standard model at various altitude. The difference between measured and the 'standard' model is almost 25% at the altitude of 37Km high, and this corresponds to the 5% difference of scale hight.

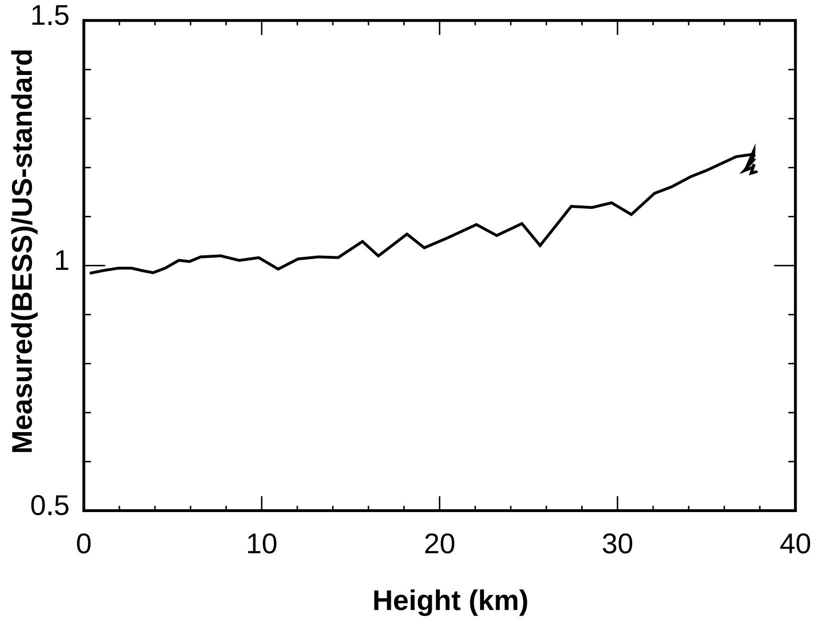

Figure 3: The atmosphere pressure ratio: measured and US-standard at high altitude. The measurements were made by on board pressure gauge and GPS position sensor in 1997 BESS flight at Lynn Lake (Orito, S. 1998)

The averaging over the observation period of the atmospheric neutrino, all the variation of column density ($\simeq$ sea level pressure) will be smeared to the average value. However, the lattitude dependence will remain just by averaging over the azimal direction. Thus, for the study of the uncertainty of the atmospheric model, we consider the 10while keeping the column density constant.

5 Atmpospheric Neutrino Flux

Since the variatoin of absolute values of the atmospheric neutirno flux varies largely with the primary flux model with the hadronic interaction model, we concentrate on the shape variation of the angular dependence. For this purpose we have calculated the variation of the ratio vertical flux to horizontal fulux for each model variation. The results are shown in Fig.4 for electron neutrinos and muon neutirnos.

We first note that the larger variation above 30 GeV for muon neutrino is due to the statistics of Monte Calro simulation. (We have simulated 10,000,0000 cosmic rays for each variation of the models.)

It is seen that the largest effect for the electron neutrino angular dependence shape comes from the atmospheric density structure. Except for the atmospheric density structure for electron neutino the variation is smaller than 3 % below 10 GeV. For the muon neutirnos, the effect of atmospheric density structure is rather small, and the variation is smaller than 5 % below 30 GeV.

6 Summary and discussion

In this paper, the effect of uncertainty of the primary cosmic ray and hadronic interaction model on the angular dependence are studied. Although the absolute values of the atmospheric neutirno may vary with the primary cosmic ray model and hadronic interaction model, It is seen that the vertical/horizontal flux ratio does not largely vary with the variation of those uncertain models. This fact may be interpretted that the shape of the atmospheric neutrino flux angluar dependence does not change largely by the change of primary cosmic ray and hadronic interaction models.

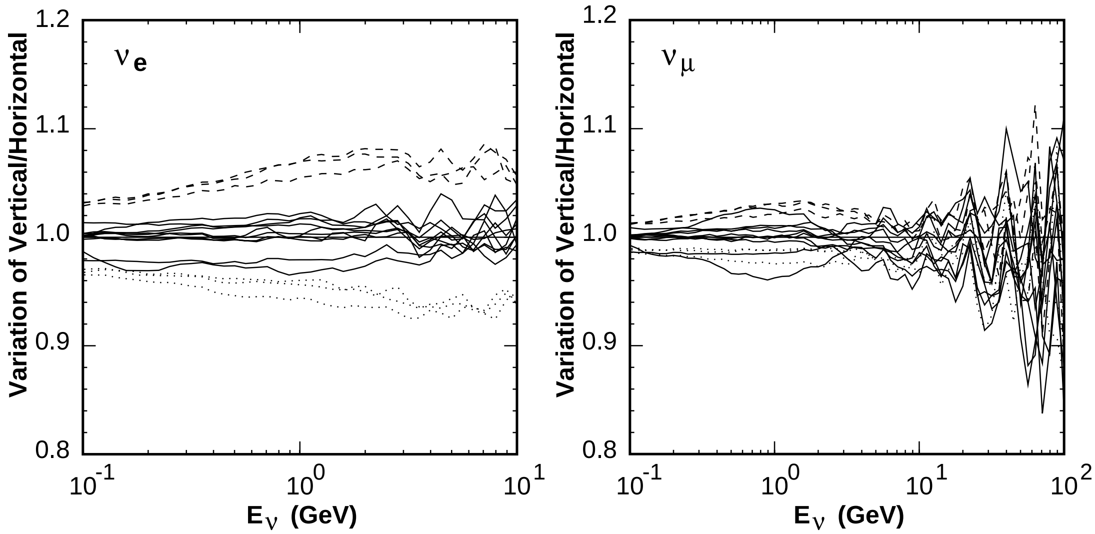

Figure 4: The variation of (vartical flux)/(horizontal flux) for ν_e. Dashed lines are for the atmospheric model with 10 % larger scal height and dots for 10 % smaller scale height. Each 3 line stands for high, mid, and low primary flux model. Other lines near (vartical flux)/(horizontal flux) ~ 1 are variation for the interaction model variation.

We note that the variation considered here probably is larger than what is generally believed, for example, 20 % uncertainty of multiplicity and 10 % of scale height. Therefore we may expect much smaller uncertainty for the shape of atmospheric neutirno angular dependence.

The energy region studied here corresponds to the Sub-GeV and Multi-GeV experiments of SuperKamiokande expereiments. Therefore, one can safely apply the 'over all normalization' to the expectation value and calculate the neutrino mass difference and mixing anlge. This study may also be applied to the up-going muon study. Above the energy we studied here, the kaon contribution becomes large. However, we estimate the variation due to the π/K-ratio uncertainty is smaller than 10 % even above $E_\nu > 100$ GeV.

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