A Precise Three-Dimensional Calculation of the Atmospheric Neutrino Flux

M.Honda,[1] K.Kajita,[1] K.Kasahara,[2] and S.Midorikawa[3]
(1) Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
(2) Shibaura Institute of Technology, Fukasaku, Ohmiya, Saitama 330-870, Japan
(3) Faculty of Engineering, Aomori University, Aomori 030-0943, Japan.

Abstract

We present here a detailed 3-dimensional calculation of the atmospheric neutrino flux in the realistic geomagnetic field. We introduce no simplification based on the symmetry, but a faster computer system with a faster simulation code. The results here generally confirm previous studies. However, we found some differences due to the difference of geomagnetic field model.

1. Introduction

The discovery of the neutrino oscillations and the neutrino masses using the the atmospheric neutrinos is a significant milestone in the recent physics. Now the detailed study of neutrino characteristics is important. However, the uncertainty of the atmospheric neutrino flux is a crucial limiting factor in the study. There are some works to reduce the uncertainty of interaction model using the secondary cosmic rays[1,2]. However, uncertainty due to the calculation scheme 1-dimensional and 3-dimensional is difficult because of the very bad efficiency of 3-dimensional calculation $\sim$ (Size of Detector/Radius of Earth)^2. The simplified geomagnetic field model and the use of the symmetry are the common idea to increase the efficiency [3,4].

In this paper, we present a straight forward approach for the 3-dimensional calculation of the atmospheric neutrinos with the multi-pole expanded realistic geomagnetic field. A similar approach is seen in the work of Tserkovnyak et al. [5], but the small efficiency is a crucial disadvantage in this approach. To complete the study, we have developed a faster simulation code, and use a faster computer system. Also the proper selection of the simulation conditions is important.

Our target is the calculation of atmospheric neutrino with 10^{11} cosmic rays. In this report, however, we present the results with 6×10^9 cosmic rays corresponding to ~ 4 nsec in the real world. Note, the number of neutrinos used in this study already exceeded that of our previous study[4].

---

pp. 1415–1418

2. Simulation code for speed

In the Monte Carlo simulation of cosmic rays in the air, the hadronic interaction code is the most time consuming parts. Here, we employ an inclusive hadronic interaction code, which does not conserve the quantities such as energy or momentum in each interaction. However, The quantities are conserved in the statistical sense, or when they are averaged over a large number of interactions.

The main body of the inclusive interaction code is a set of tables of all the secondary particle energy spectra for all the hadronic interacting projectiles and energies, in the hadronic interaction with air nuclei. We consider all the hadrons as the hadronic interacting particles, but ignored the hadronic interaction caused by the leptons and gamma-rays. We constructed the tables for the projectile energies from 0.2 GeV to 100 TeV in the half decade steps, and applied an interpolation for the energies between two neighboring steps.

This structure of inclusive code make it easy to work with a different hadronic interaction model, if the set of tables is already constructed. Although the tables for dpmjet3, FLUKA 97, Fritiof 1.6, and Fritiof 7.02 are ready, we work only with dpmjet3, as it is the most favored interaction model by the muon and gamma ray observations at the balloon altitude [1,2].

Note, the simulation code with the inclusive interaction engine is only useful for the average value resulted from a large number of primary cosmic rays. This is exactly the case for the atmospheric neutrino flux. However, it is not valid for a phenomena caused by a single particle, such as air shower events.

3. Simulation conditions

We inject the cosmic rays with kinetic energies above 1 GeV at the altitude of 100km asl, when they pass the rigidity cutoff test. All the particle including the secondaries and decay products are traced until they go outside of the simulation boundary, or they encounter the earth. The boundary of the simulation is set at the altitude of 300km asl. The primary flux model is basically that of Gaisser et al.[6]. However, we applied a little modification (spectral index -2.70 above 100 MeV) for proton cosmic rays, so that it goes through the center of the data at above 10 TeV.

Even with many techniques for the fast computation, the efficiency of 3-dimensional is still very bad. Therefore, We assume a circle whose radius is 900km and the center is the target site on the surface of the Earth, and all the neutrinos go through inside the circle is registered. Presently, the target sites are Kamioka, SNO, and Gran Sasso, but the results for Kamioka only are shown in this paper.

4. Results and comparison with previous calculation

In Fig. 1, we present the neutrino flux averaged over all directions for Kamioka site. The solid lines are the present results and the marks are that of previous study [4]. In our previous study, we take the interaction model based on the Fritiof 1.6, and the primary spectra model is very similar to the present model. As the results, we find a similar feature with the muon flux comparison calculated with Fritiof 1.6 and dpmjet3, that the result with Fritiof 1.6 is larger than that with dpmjet3 at lower energies, but they are reversed at energies above a few GeV.

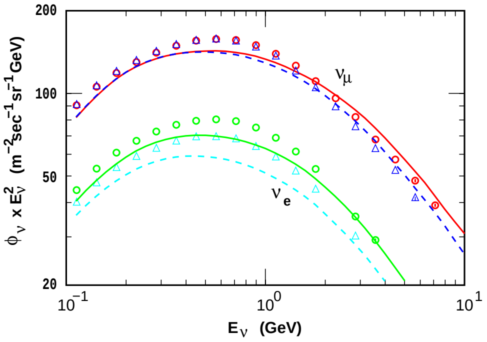

Fig. 1. All direction averaged neutrino flux for Kamioka.

We plotted the neutrino flux as a function of zenith angle in Fig. 2 and as a function of azimuth angle in Fig. 3, with the result of ref. 4. In these figures, we take the logarithmic vertical axis to separate the difference of normalization from others. The amplitude of horizontal enhancement is larger for present calculation. This is considered due to the difference interaction model. The average transverse momentum of pions is ~ 0.28 for Fritiof 1.6, and 0.32 for dpmjet3 at proton energy of 30 GeV in proton – air interactions. Also the variations over zenith angles and azimuth angels are a little different between previous and present ones. This is the reflection of the difference of geomagnetic field model, dipole or multi-pole.

The cumulative distribution of angles between neutrinos and primary cos-

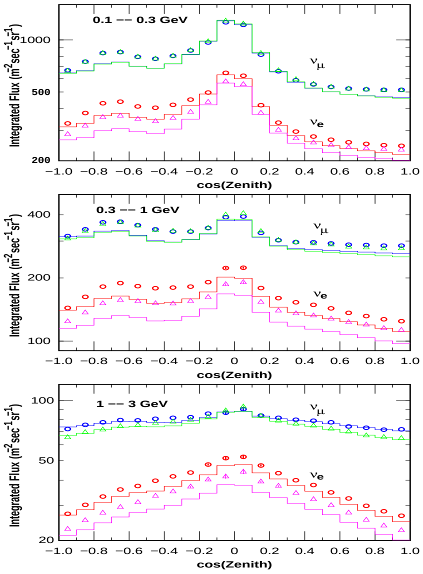

Fig. 2. Variation of neutrino flux as a function of zenith angle

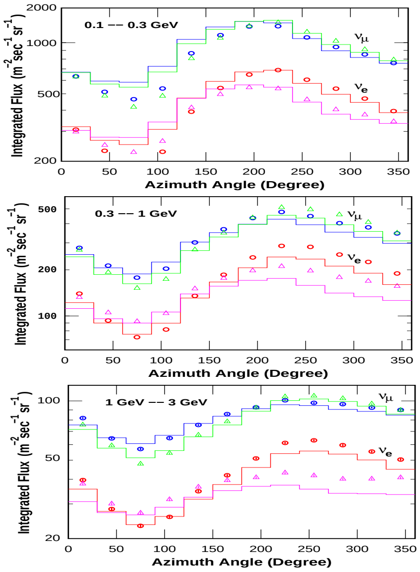

Fig. 3. Variation of neutrino flux as a function of azimuth angle

mic rays is shown in Fig. 4 for near vertical directions and in Fig. 5 for near horizontal directions. It is seen that the the angle distribution for horizontal directions does not shrink so quickly with the neutrino energy as the vertical directions. However, for the neutrino energies above 10 GeV, the distribution is narrow enough, and the 1-dimensional approximation is justified.

5. summary

With a fast computer system and faster simulation code, we are carrying out a detailed study of the 3-dimensional calculation of the atmospheric neutrino flux in the realistic geomagnetic field. The neutrino fluxes calculated in the dipole and multi-pole magnetic fields show a little but visible differences. For neutrino energy below 10 GeV, one need a 3-dimensional calculation similar to this paper. For the neutrino energy above 10 GeV, one may use the 1-dimensional approximation for a better efficiency.

We would like to thank T. Sanuki and BESS collaboration for discussions and support. We also thank to ICRR, the University of Tokyo for the support. This study was supported by Grants-in-Aid, KAKENHI(12047206), from the Ministry of Education, Culture, Sport, Science and Technology (MEXT).

1. Kasahara K. et al. 2002, Phys. Rev. D66:052004
2. Abe K. et al. this conf., and astro-ph/0304102, 2003, Phys. Lett. B, in press
3. Battistoni G. et al. 2000 Astropart. Phys. 12, 315
4. Honda M., Kajita T., Kasahara K., Midorikawa S. 2001 Phys. Rev. D64:053011
5. Tserkovnyak Y. et al. hep-ph/9907450
6. Gaisser T.K., et al. 2001 ICRC Hamburg.

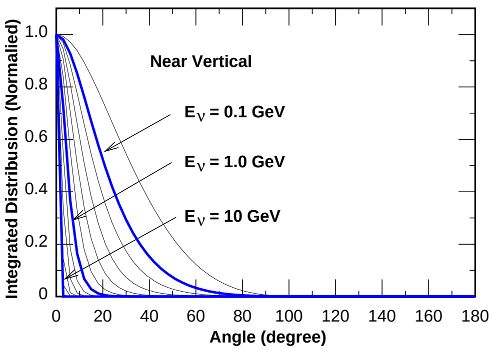

Fig. 4. Cumulative angle distribution between neutrinos and primary cosmic rays for near vertical directions

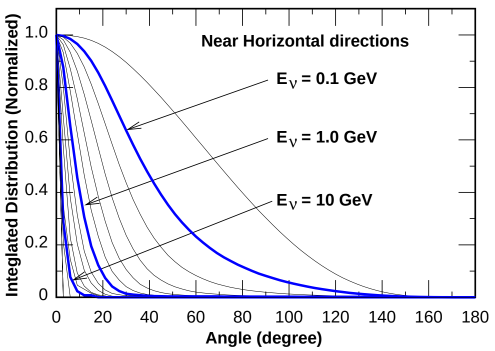

Fig. 5. Cumulative angle distribution between neutrinos and primary cosmic rays for near horizontal directions