3-Dimensional Simulation of Atmospheric Muon and Neutrino Flux

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Abstract

The atmospheric muon and neutrino flux have been calculated by a full 3-dimensional simulation. For muon flux, the results are in good agreement with the recent CAPRICE,HEAT and BESS data ranging from sea level to the highest float altitude. The features of the calculated atmospheric neutrino around the Super-Kamiokande detector are reported. In particular the East-West asymmetry for neutrino is discussed.

1. Simulation

With the rapidly increasing amount and statistical significance of the data collected by underground neutrino detectors [4], the precise calculation of the atmospheric neutrino flux is highly desirable. To this purpose, an event generator describing the CR induced cascade in the atmosphere, particle propagation in geomagnetic field, and interactions with the medium, has been used. This code was successfully used to reproduce the proton, electron-positron and helium 3 [1] flux data measured by AMS and their relevant dependence on the geomagnetic coordinates. Since the $e^{\pm}$ generator of the program was basically the same as needed to generate the muon and neutrino flux, the code could be rather straightforwardly extended to describe the latter and to address the important issue of the atmospheric neutrino flux.

The calculation use the 1998 AMS measurement of incident CR proton and helium flux. The kinetic energy range of incident CRs covered in the simulation is $[0.2, 2000]$ GeV. Each particle is propagated in the geomagnetic field and interacts with nuclei of the local atmospheric density. Every secondary particles are processed the same way as their parent particle, leading to the generation of atmospheric cascades. Nucleons, pions and kaons are produced with their respective cross sections (see ref. [6]). For the decay of muons, the spectra of the products $(\nu, \bar{\nu}, e^{\pm})$ are generated according to the Fermi theory and the muon polarization was taken into account.

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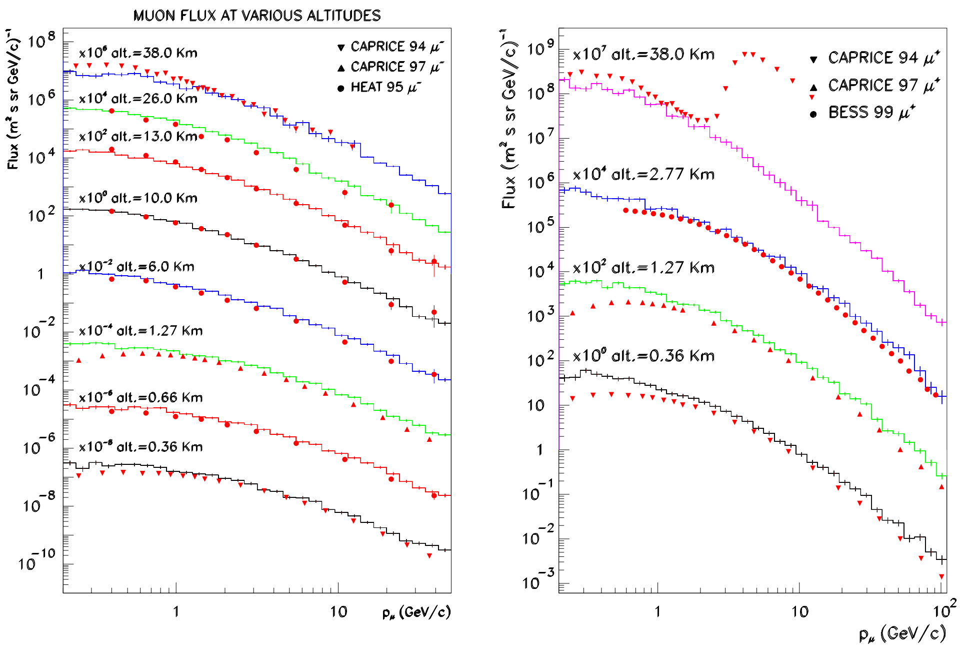

Fig. 1. Simulation results (histograms) for the negative muon (left) and positive muon (right) flux at various altitudes in the atmosphere, compared to measurements (full circles and triangles), from sea level up to about 38 km. See text for details.

2. Muon flux in the atmosphere

Atmospheric muons are produced in the same reaction chain as neutrino and is then an essential probe to support the reliability of the neutrino flux calculated in the same framework. Figure 1. shows the calculated muon flux compared to the data measured by the CAPRICE, HEAT and BESS experiments [2] at various altitudes. For negative muons the agreement between simulation results and data is quite good through the energy range investigated (0.5-50) GeV for all altitudes, from about the sea level to 38 km. It is especially good over the region from 10 km to 26 km altitude where a large fraction of the neutrinos detected by underground detectors are produced (see below). For positive muons the agreement with the BESS 99 data at mountain altitude is very good, but in the low (below 1.0 GeV) and high (beyond 10.0 GeV) energy range, the departure is obvious. This may result from the overestimation of the secondary proton/neutron production cross section at low energy and pion/kaon production cross section at high energy.

3. Neutrino flux at the SK site

The calculated energy distributions of the atmospheric neutrino flux and the $\nu/\bar{\nu}$ flux ratios around the SuperK detector, averaged over 4π solid angle, are compared with the results of Honda et al. [3] on figure 2., for the various flavors. The flux obtained in the present work appear to be significantly smaller than in the 1-Dimensional calculations for low neutrino energies.

For the flavor ratios, our $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ is similar to that reported in [3], but $\nu_e/\bar{\nu}_e$ differ evidently from all the previous 1-dimensional calculation summarized in figure 12 of [3].

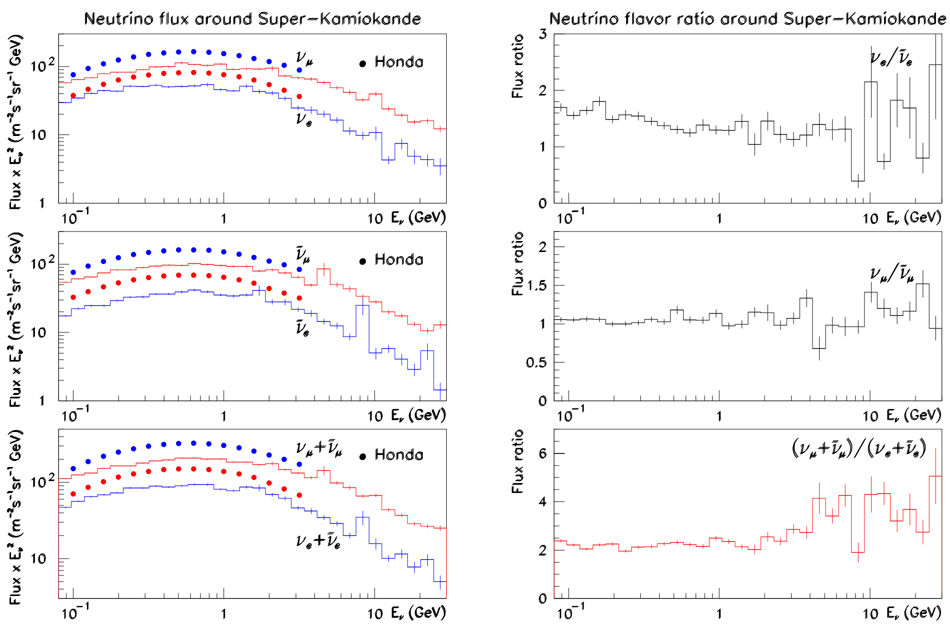

Fig. 2. Simulated atmospheric neutrino spectra and flavor ratio around the Super-Kamiokande detector.

4. East-West asymmetry at the SK site

In addition to the atmospheric muon flux, the EW asymmetry measurements provide an important global test of the reliability of the overall approach. However, the EW asymmetry is not senstative to the neutrino oscillation.

For the asymmetry parameter A_{EW} defined as:

$$A_{EW} = \frac{N_E - N_W}{N_E + N_W} \tag{1}$$

$N_E(N_W)$ being the number of eastward (westward) lepton events, the SuperK Collaboration reported the following measured values [5]:

$$A_{EW}^{e-like} = 0.21 \pm 0.04 \quad A_{EW}^{\mu-like} = 0.08 \pm 0.04$$

for e-like and μ-like events respectively, for a selection of single-ring events with momentum between $0.4 - 3$ GeV and $-0.5 \leq \cos\tau_{zenith} \leq 0.5$, with τ_{zenith} being the zenith angle.

The calculated EW asymmetries obtained for the two neutrino flux with the same cut over the zenithal angle and within the same energy bin of $[0.55, 3.1]$ GeV, are:

$$A_{E-W}^{\nu_e+\bar{\nu}_e} = 0.17 \pm 0.03 \quad A_{E-W}^{\nu_\mu+\bar{\nu}_\mu} = 0.22 \pm 0.02$$

where the larger EW flux asymmetry obtained for $\nu_\mu(\bar{\nu_\mu})$ than for $\nu_e(\bar{\nu_e})$ can be qualitatively understood: The production of $\nu_e(\bar{\nu_e})$ takes place in the second step of the pion decay chain.

In order to obtain the A_{EW} for $e-like$ and $\mu-like$ events, the 3-Dimension differential neutrino reaction cross section needs to be taken into account which gives [6] :

$$A_{E-W}^{e-like} = 0.12 \pm 0.03 \quad A_{E-W}^{\mu-like} = 0.13 \pm 0.02$$

which shows that the predicted neutrino asymmetry is largely washed out by the angular distribution of the neutrino induced lepton production process.

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