Characterizing the Atmospheric Neutrino Flux

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Abstract

The atmospheric neutrino data of the Super-Kamiokande detector were analyzed to characterize the atmospheric neutrino flux. 1) The ratio between ν_μ flux and $\bar{\nu}_\mu$ flux is obtained and it is consistent with existing calculations. 2) The east-west asymmetry of the atmospheric neutrino flux is also obtained for e-like and μ-like events separately. They are consistent with calculations that account for the geomagnetic field. 3) We examined possible correlations of the atmospheric neutrino events with solar activity. The data can be explained both with or without the effect of solar activity.

1. Introduction

The Super-Kamiokande (SK) detector gives us an opportunity to characterize the atmospheric neutrino flux. The analyses shown here are based on 1489 days data sample which were recorded during the whole of SK-I from May 27, 1996 to July 16, 2001. The detector is described in detail elsewhere [1].

2. Ratio between ν_μ flux and $\bar{\nu}_\mu$ flux

The atmospheric neutrino calculations give almost equal fluxes for ν_μ and $\bar{\nu}_\mu$ less than 10 GeV [2,3]. It is important to check the calculation by observation.

To determine the flux ratio between ν_μ and $\bar{\nu}_\mu$, we utilize the difference of the fraction of observing a decay electron from a produced μ^+ and μ^- in the water [4]. Since a proton or an oxgyen nucleus captures μ^-, it can decay without emitting a decay electron. On the other hand, μ^+ always gives a decay electron. Therefore we can determine the flux ratio from the fraction of observing a decay electron from a produced muon.

We selected a total of 3181 fully-contained Sub-GeV single-ring μ-like events from the data set. A decay electron is searched for after 1.2 μs from the observed parent lepton since the systematic error of the detection efficiency in that time region is minimum. 1327 events (41.7%) are accompanied by only one decay electron. We also examined our 70 yr Monte Carlo (MC) with neutrino

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oscillations ($\Delta m^2 = 2.5 \times 10^{-3}\,\mathrm{eV}^2$, and $\sin^2 2\theta = 1$) to predict the fraction of observing a decay electron after a ν_μ interaction and a $\bar{\nu}_\mu$ interaction. If we define:

$$\text{e-tag fraction} \;=\; \frac{(n_\mu + \bar{n}_\mu)\left(r\dfrac{\tilde{n}_\mu}{n_\mu} + (1-r)\dfrac{\tilde{\bar{n}}_\mu}{\bar{n}_\mu}\right) + \tilde{n}_{\mathrm{BG}}}{n_\mu + \bar{n}_\mu + n_{\mathrm{BG}}}, \qquad (1)$$

where n_μ ($\bar{n}_\mu$) is the number of the ν_μ ($\bar{\nu}_\mu$) induced events, $\tilde{n}$ shows the number of events accompanied with a decay electron. n_{BG} is the ν_e or $\bar{\nu}_e$ induced background events. r is $n_\mu/(n_\mu + \bar{n}_\mu)$. If we give the e-tag fraction from data, we can obtain r_{data}. The flux ratio $\Phi(\bar{\nu}_\mu)/\Phi(\nu_\mu)$ can also be obtained as $(1/r_{\mathrm{data}} - 1)/(1/r_{\mathrm{MC}} - 1)\Phi(\bar{\nu}_\mu)/\Phi(\nu_\mu)|_{\mathrm{MC}}$ if we assume the energy spectra for neutrinos are well reproduced in MC. $\Phi(\bar{\nu}_\mu)/\Phi(\nu_\mu)|_{\mathrm{MC}} = 0.98 \pm 0.02$ for the interested energy region.

We also estimated systematic errors of r both for data and MC prediction. The error for the data and MC dominates the uncertainty of the decay electron finding efficiency and neutrino cross sections, respectively. Then we obtained $r_{\mathrm{data}} = 0.73 \pm 0.06\,(\mathrm{stat.}) \pm 0.05\,(\mathrm{syst.})$, $r_{\mathrm{MC}} = 0.74 \pm^{0.04}_{0.07}\,(\mathrm{syst.})$, and $\Phi(\bar{\nu}_\mu)/\Phi(\nu_\mu) = 1.03 \pm 0.32\,(\mathrm{stat.}) \pm^{0.35}_{0.47}\,(\mathrm{syst.})$, which means our observation is consistent with the atmospheric neutrino calculations.

3. East-West Asymmetry of the Atmospheric Neutrino Flux

Although the primary cosmic rays approaching the Earth are known to be isotropic, an angular anisotropy is produced by the magnetic field of the Earth. We have observed this anisotropy, called the east-west effect in the flux of atmospheric neutrinos [5]. Here we update the result.

In Fig. 1, the azimuthal angle distribution of e-like and μ-like events are shown. The azimuthal angles are divided into 8 bins, 45 degrees each. The χ^2 values between the data and MC were 12.4/7 d.o.f. and 5.3/7 d.o.f. for e-like and μ-like events, respectively. The east-west asymmetry of the data $(N_e - N_w)/(N_e + N_w) = 0.16 \pm 0.03\,(\mathrm{stat.})$ and $0.07 \pm 0.03\,(\mathrm{stat.})$ for e-like and μ-like events, respectively. The corresponding expected values are 0.11 and 0.12 for the flux in [2], and 0.15 and 0.15 for the flux in [3]. The east-west asymmetry as a function of lepton momentum is also examined. The χ^2 between data and MC is 5.8/6 (4.9/5) for e-like (μ-like) events. The χ^2 of a comparison of the data and a straight line were 30.8/6 (10.3/5) for e-like (μ-like) events.

Thus the azimuthal distribution of e-like and μ-like events agrees with the expectation from calculations that account for the geomagnetic field. This strongly indicates that the effects of the geomagnetic field on the production of atmospheric neutrinos in the GeV energy range are well understood.

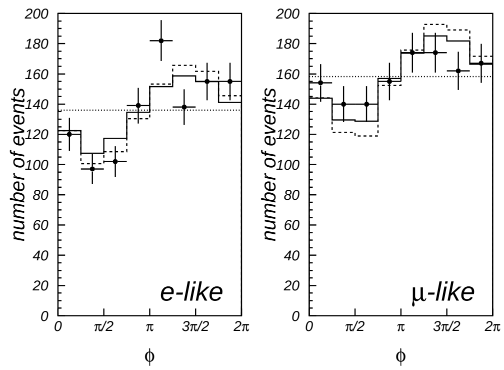

Fig. 1. The azimuthal angle distribution of e-like and μ-like events. The crosses represent the data, the solid line (dashed line) is the prediction of the MC based on the flux [2] ([3]). ϕ represents the azimuthal angle. $\phi = 0, \pi/2, \pi$ and $3\pi/2$ shows particles going to north, west, south, and east, respectively.

4. Solar Modulation

Since the flux of the primary cosmic-ray intensity depends on the magnetic field and therefore solar activity, there exists an eleven year cycle of cosmic ray modulation. Since atmospheric neutrinos originate from the cosmic rays, it is valuable to see the possible modulation of atmospheric neutrinos during a long time observation. Fig. 2 shows the event rate of the observed neutrino signals. It does not give any significant distortion from a constant rate.

To obtain the expected modulation, we used the Climax data [6] and the neutrino flux at solar minimum and solar maximum [2]: expected $= r f_{\min} + (1 - r) f_{\max}$, $r = (c_{\max} - c)/(c_{\max} - c_{\min})$, where $f_{\min}$ and $f_{\max}$ is the neutrino flux at solar minimum and at solar maximum, c, $c_{\min}$, and $c_{\max}$ is the Climax data, the Climax data at solar minimum (4.28×10^5/hr), and the Climax data at solar maximum (3.27×10^5/hr), respectively.

The Kolmogorov-Smirnov test was applied to the data and the modulated MC. The results shown in Tab. 1 indicate that the data can be explained both with or without the effect of the solar activity. The main reason of the difficulty is that the primary cosmic ray energies which generate most of the neutrinos seen in SK are from higher energies (above 10 GeV) than the Climax neutron monitor (around 1 GeV).

5. Summary

We obtained the flux ratio between ν_μ and $\bar{\nu}_\mu$, and the east-west asymmetry of e-like events and μ-like events. They are consistent with the calculations. We also tested the possible modulation of atmospheric neutrino data with solar

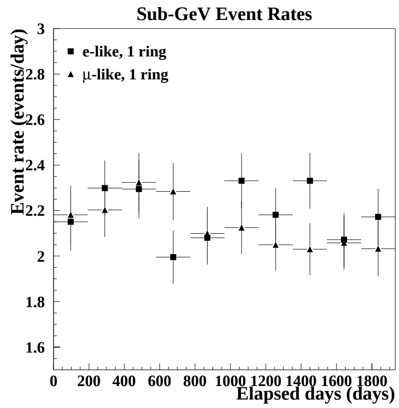

Fig. 2. Event rates for Sub-GeV 1 ring e-like events and μ-like events at at SK.

Table 1. The KS probability of data vs. (a) a constant rate hypothesis, and (b) solar modulated MC events. The modulated MC based on the Honda 1D calculation with neutrino oscillations. [2]

Events	num. of events	(a) flat (%)	(b) solar modulated (%)
Sub-GeV, 1 ring	6447	28.7	85.8
Sub-GeV, 1 ring, e-like	3266	75.7	20.0
Sub-GeV, 1 ring, μ-like	3181	4.0	14.1
Multi-GeV, 1 ring	1436	43.3	37.4
Multi-GeV, 1 ring, e-like	772	41.1	24.8
Multi-GeV, 1 ring, μ-like	664	85.0	90.0

activity. The result can be explained both with or without the modulation.

6. References

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6. Data compiled from the CLIMAX neutron monitor, http://ulysses.uchicago.edu/NeutronMonitor/neutron_mon.html. We gratefully acknowledge the continuous measurement by University of New Hampshire, National Science Foundation Grant ATM-9912341.