Measurements of the atmospheric neutrino flux by Super-Kamiokande: energy spectra, geomagnetic effects, and solar modulation

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Abstract. A comprehensive study on the atmospheric neutrino flux in the energy region from sub-GeV up to several TeV using the Super-Kamiokande water Cherenkov detector is presented. The energy and azimuthal spectra of the atmospheric $\nu_e$ and $\nu_\mu$ fluxes are measured. The energy spectra are obtained using an iterative unfolding method by combining various event topologies with differing energy responses. The azimuthal spectra depending on energy and zenith angle, and their modulation by geomagnetic effects, are also studied. A predicted east-west asymmetry is observed in both the $\nu_e$ and $\nu_\mu$ samples at 8.0$\sigma$ and 6.0$\sigma$ significance, respectively, and an indication that the asymmetry in dipole angle changes depending on the zenith angle was seen at the 2.2$\sigma$ level. The measured energy and azimuthal spectra are consistent with the current flux models within the estimated systematic uncertainties. A study of the long-term correlation between the atmospheric neutrino flux and the solar magnetic activity cycle is also performed, and a weak preference for a correlation was seen at the 1.1$\sigma$ level, using SK I-IV data spanning a 20 year period. For particularly strong solar activity periods known as Forbush decreases, no theoretical prediction is available, but a deviation below the typical neutrino event rate is seen at the 2.4$\sigma$ level. Please refer to [1] for more detailed descriptions about the analysis shown in this paper.

1. Energy spectrum measurement
The motivation of this study is to improve the measurement of atmospheric neutrino energy spectrum from 100 MeV up to 10 TeV and test flux calculation models such as HKKM, Bartol, Fluka with data. The precise energy spectrum is necessary for rare event search such as proton decay, WIMP, astronomical neutrino. Also possible future analysis combined with higher energy data, such as IceCube, is expected. We employ high purity $\nu_e$ and $\nu_\mu$ data of Super-Kamiokande sample for $\nu_e$ and $\nu_\mu$ measurement, respectively. An iterative Bayesian unfolding is adopted to reconstruct true energy spectrum. This unfolding method is validated by pseudo data and incompleteness is considered as systematic error. The total systematic errors are estimated to be approximately 20% uncertainties, among of them the uncertainties related to neutrino interaction is dominant. Figure 1 shows the measured energy spectra of atmospheric $\nu_e$ and $\nu_\mu$ fluxes by Super-Kamiokande shown with other measurements. The measured spectrum is consistent with flux models within estimated uncertainties.
2. Azimuthal spectrum analysis

The primary cosmic rays are deflected by the Earth’s geomagnetic field, and suffer from the rigidity cutoff depending on the detector site. Then an east-west anisotropy of the atmospheric neutrino flux is expected as well as in cosmic ray protons. The anisotropy is anticipated to becomes larger around GeV region and near horizontal directions. Using the atmospheric neutrino data it is possible to test the geomagnetic effect in the flux calculation, such as the bending of the primary and secondary cosmic ray particles, by measuring such anisotropy. Figure 2 shows azimuthal spectra of $e$-like and $\mu$-like data. The cut criteria for the energy and zenith angle are optimized for getting the largest significance. You can see clear asymmetry for both $\mu$-like ($6.0\sigma$) and $e$-like ($8.0\sigma$) sample. The energy and zenith dependence of azimuthal asymmetry are also investigated in more detailed, and it is found that data and the predictions agree well confirming implementation of geomagnetic field in flux calculation.

3. Search for correlation with solar activity

Cosmic ray flux is known to be anti-correlated with the solar activity, which cycles in 11 year’s period, since solar wind scatters out cosmic ray. Accordingly modulation of the atmospheric neutrino flux by solar cycle is expected. Since Super-Kamiokande I-IV data covers almost two solar cycles, we search for the correlation with the solar activity. In order to estimate solar activity in the observed time, we employ neutron monitor count which is known to be well correlated with cosmic ray flux. The expected flux changes as a function of neutrino energy and direction is obtained from the flux calculation research group. The flux is affected in low energy and around polar regions.

Figure 3 shows the observed rate of single-ring sub-GeV event as a function of neutron monitor count $C$. We introduce $\alpha$ parameter to model the degree of flux modulation, in which $\alpha=0$ and 1 corresponds to no correlation and as predicted, respectively. The best fit lies $\alpha=0.62^{+0.57}_{-0.58}$ and weak correlation ($1.1\sigma$) is preferred between neutrino data and solar activity. Also seasonable
Figure 2. Azimuthal distributions of a subselection of $e$-like (left) and $\mu$-like (right) events, from the SK-I-SK-IV data (points with statistical error) and MC simulations (boxes with systematic error). The subselection is optimized to obtain the highest significance of the final $A$ parameters, by using only events with $0.4 < E_{\text{rec}} < 3.0$ GeV and $|\cos\theta_{\text{rec}}| < 0.6$.

variation of the atmospheric neutrino due to the variation of the atmosphere density in the air is investigated though expected to be small (<1%). No seasonal variation is seen as expected.

Figure 3. The test for a solar modulation correlation using the SK-I-SK-IV data (points). The solar correlation hypotheses are shown for no correlation ($\alpha=0$,grey), best fit ($\alpha=0.62$,red), and the default prediction ($\alpha=1$,grey dotted) for each of the four data samples.

References
[1] E. Richard et al., Measurements of the atmospheric neutrino flux by Super-Kamiokande: energy spectra, geomagnetic effects, and solar modulation, Phys. Rev. D94(5), 052001 (2016). 10.1103/PhysRevD.94.052001.