Atmospheric Muon Fluxes at Various Locations

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Abstract

In order to study neutrino oscillation phenomena using atmospheric neutrinos, it is crucially important to calculate their absolute fluxes and spectral shapes accurately. Since production and decay processes of muons are accompanied by neutrino production, observation of atmospheric muons gives fundamental information about atmospheric neutrinos. We made a series of observations of atmospheric muons. Hadronic interaction models were studied using the data of primary and secondary cosmic rays observed with the BESS spectrometer.

1. Introduction

Neutrino oscillation was discovered in the atmospheric neutrinos [1]. The next step is accurate determination of the oscillation parameters. However, the capability of neutrino studies using the atmospheric neutrinos is limited by the accuracy of the predicted neutrino fluxes.

The atmospheric neutrino flux of flavor i (ϕ_{ν_i}) can be expressed as

$$\phi_{\nu_i} = \phi_p \otimes R_p \otimes Y_{p\to\nu_i} + \sum_A \phi_A \otimes R_A \otimes Y_{A\to\nu_i}, \tag{1}$$

where $\phi_{p(A)}$, $R_{p(A)}$ and $Y_{p(A)\to\nu_i}$ are the flux of primary protons (nuclei of mass A) outside the influence of the geomagnetic filed, the effect of the geomagnetic field and the yield of neutrinos per primary particle, respectively [2]. The factor $Y_{p(A)\to\nu_i}$ includes composite process; hadronic interaction with air nuclei, propagation in the atmosphere, and decay of secondary particles. In order to improve accuracy of the atmospheric neutrino calculation, all these factors have to be known precisely. Measurement of both primary and atmospheric cosmic rays at various sites will improve our understanding of $\phi_{p(A)}$, $R_{p(A)}$ and $Y_{p(A)\to\nu_i}$.

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2. Atmospheric Neutrino Calculation

In the atmosphere, muons are being produced and decaying through following processes:

$$p/A + \mathrm{Air} \rightarrow \pi + \pi + \cdots, \tag{2}$$

$$\pi \rightarrow \mu + \nu_\mu, \tag{3}$$

$$\mu \rightarrow e + \nu_e + \nu_\mu. \tag{4}$$

Absolute flux of primary cosmic ray is the most fundamental information for the calculation of atmospheric neutrinos. Very precise measurement of primary cosmic-ray spectra up to around 100 GeV had been carried out by AMS and BESS experiments [3, 4, 5]. During space shuttle flight, the AMS experiment directly observed the effect of the geomagnetic field on primary cosmic rays, $R_{p(A)}$ [4, 6]. Although the AMS and BESS experiments are fully independent experiments, the resultant spectra show extremely good agreement with each other. The BESS spectrometer was upgraded to be equipped with new tracking detectors so as to improve its resolution in momentum measurement. The upgraded spectrometer, BESS-TeV, succeeded in measuring primary proton and helium spectra up to 540 GeV and 250 GeV/n, respectively [7]. The primary cosmic rays in this energy range are relevant to atmospheric neutrinos observed as "contained events" in Super-Kamiokande. Thus it seems reasonable to suppose that we already know the $\phi_{p(A)}$ and $R_{p(A)}$ in Eq. (1) with sufficient accuracy for estimating an event rate of "contained events."

At present, the main uncertainty in the calculation of the atmospheric neutrino flux stems from hadronic interactions, $Y_{p(A)\rightarrow\nu_i}$. There are scarcely any recent experiments available for studying hadronic interactions. Since the production and decay process of muons are accompanied by neutrino production as shown in Eqs. (2) – (4), the observation of the muons at various altitudes will give us information about atmospheric neutrino production.

3. Muon Measurement in the Atmosphere

Atmospheric muons have been measured at various locations by using ground-based as well as balloon-borne instruments. From the viewpoint of experimental technique and related physics process, these flux measurement can be categorized into:

(i) muon measurement on the ground,

(ii) muon measurement in the atmosphere

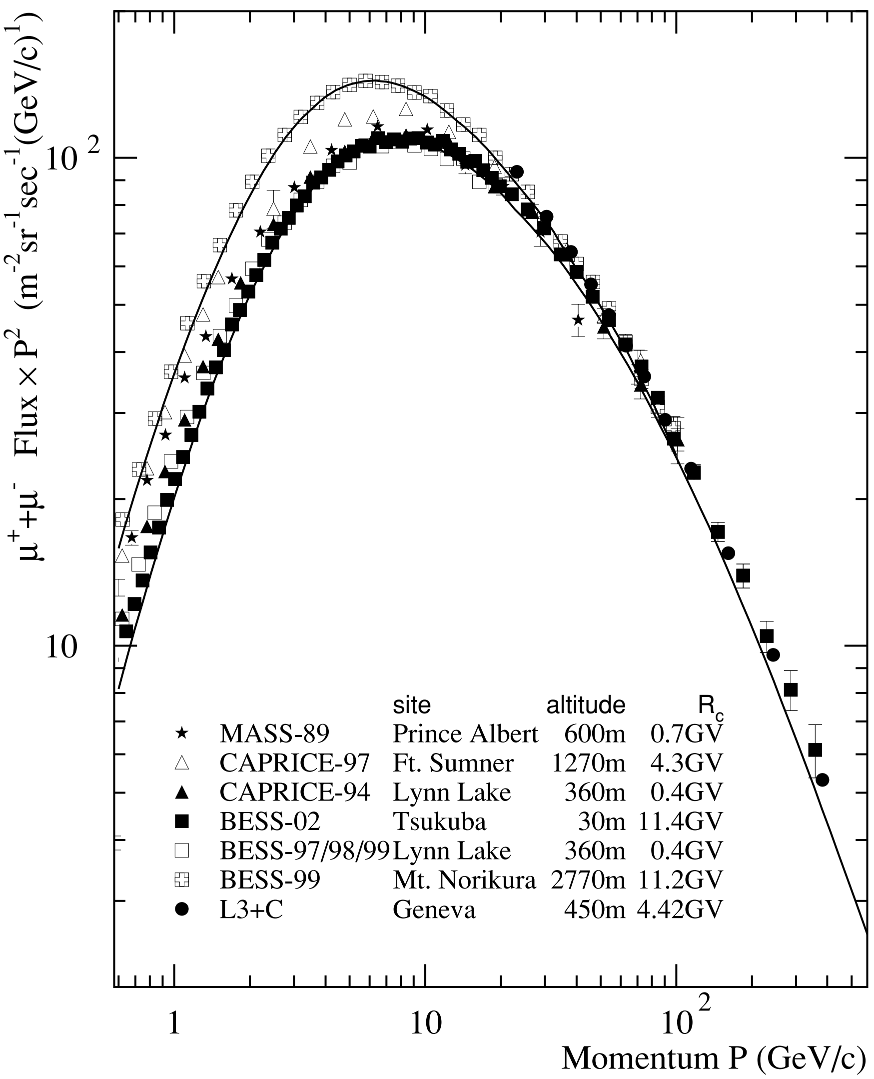

Fig 1. Observed and calculated spectra of atmospheric muon.

(iii) muon measurement near the top of the atmosphere.

A corresponding thickness of the residual air to each category is $1000-800$ g/cm^2, $800-5$ g/cm^2 and $30-5$ g/cm^2, respectively. We are observing surviving muons in Eq. (4) on the ground. Climbing up in the atmosphere, muon production processes like Eqs. (2) and (3) become dominant.

3.1. On the Ground

3.1.1. Measurement

Muons, as well as neutrinos, are the most dominant component among cosmic rays on the ground. There has been a lot of measurement of atmospheric muons on the ground [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19].

An absolute flux is calculated by dividing the number of observed muons in some momentum region by a product of the exposure factor ($S\Omega \cdot t$) and the total efficiency. Most of the previous experiment did not obtain an absolute flux but normalized their observed spectrum to the "standard" value such as "Rossi point," probably because it was difficult to precisely estimate the exposure factor and the total efficiency as a function of momentum. The "standard" value was usually measured as an integrated flux above some energy with a simple range detector.

Most of the previous measurement utilized solid iron magnet spectrometers, in which multiple scattering inside the iron made it difficult to measure the absolute rigidity reliably. In these cases, it is not trivial to measure an absolute rigidity of incoming particle event by event. Since atmospheric muons have very steep spectral shape, a small error in momentum measurement leads to a large systematic error in the absolute flux in this kind of normalization. Small flux in higher momentum region may leads to a statistical error in the "standard value." Resultant flux may suffer common systematic error if it was normalized to the same value.

In Fig. 1, there shown results of absolute flux measurement. In the measurement, superconducting spectrometers were utilized, which measured absolute flux without normalization to the "standard" value. A thickness of material inside the superconducting spectrometer is much thiner than the solid iron magnet spectrometers. Systematic errors are, therefore, expected to be well controlled to be small.

Even if the absolute flux was measured without any normalization, it would be different dependent on altitude and geomagnetic cutoff rigidity of experimental site, atmospheric structure and experimental condition such as zenith angle cut. The muon flux in a higher momentum region is almost determined by the absolute

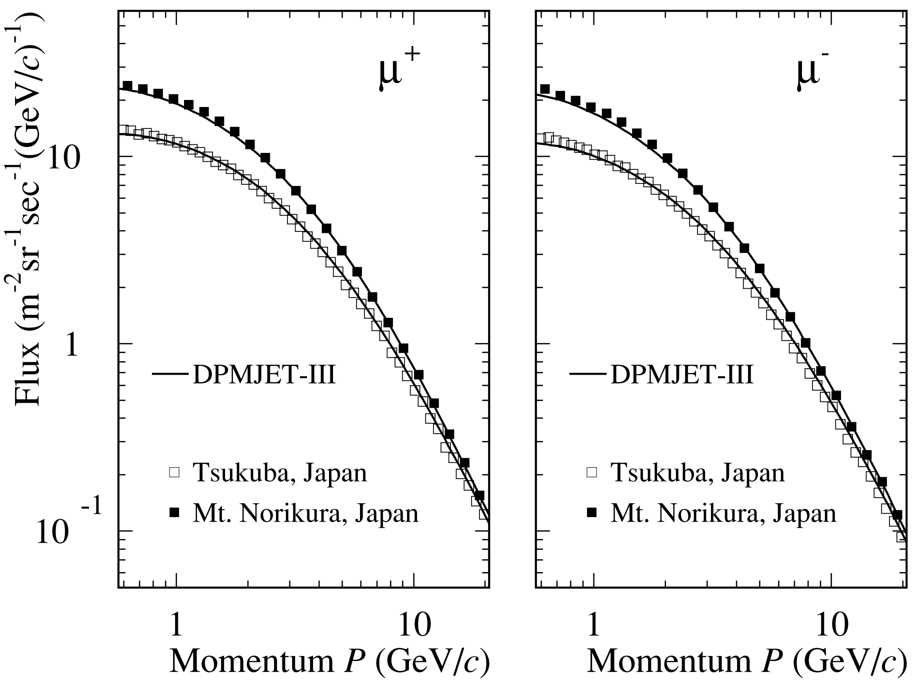

Fig 2. Observed and calculated spectra of atmospheric muon in a lower momentum region.

flux of primary cosmic ray and hadronic interaction. The spectral shape in a lower momentum region is affected by energy loss and decay of muons as well as geomagnetic field. The higher an altitude of the experimental site is, the higher flux is observed as shown in Fig. 1. As shown in Fig.2, it is clearly observed in comparison between muon spectra measured with the BESS spectrometer at sea level and mountain altitude in Japan, since other experimental conditions, such as geomagnetic cutoff rigidity and employed detector, were identical. The discrepancy among the absolute fluxes reflects the fact that muon decay process is predominant over production process near sea level.

3.2. In the Atmosphare

When we observe muon fluxes during balloon ascending period, growth curve of atmospheric muons, or correlation between muon intensity and a thickness of the residual air, will be obtained. Since the production and decay process of muons are accompanied by neutrino production as shown in Eqs. (2),(3), and (4), the observation of the muon growth curve is indirect measurement of atmospheric neutrino production. Observing the muon growth curve would be important to investigate hadronic interaction models.

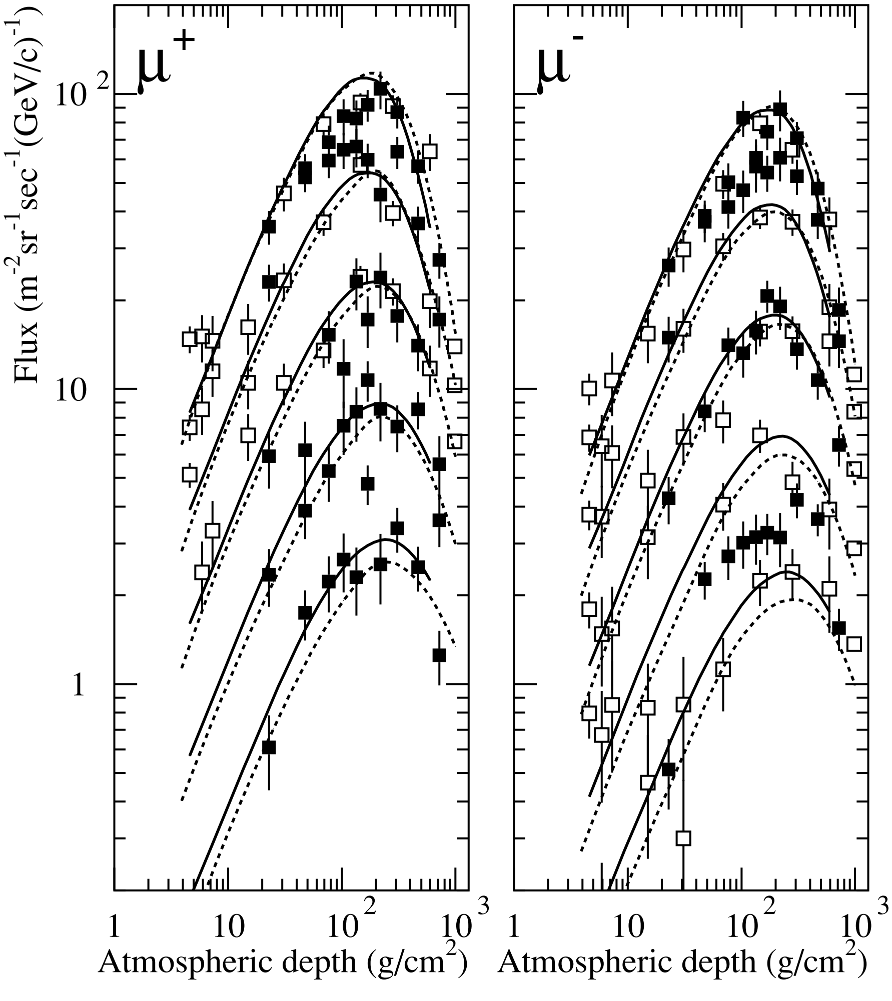

Fig 3. Atmospheric muon growth curves. From top to bottom are the momentum in GeV/c: 1.0, 1.5, 2.5, 3.9, 6.3. Closed and open squares shows data measured in CAPRICE-1998 and BESS-1998 balloon flights, respectively. Solid and dashed lines are calculated growth curves by R. Engel et al. and M.Honda et al., respectively.

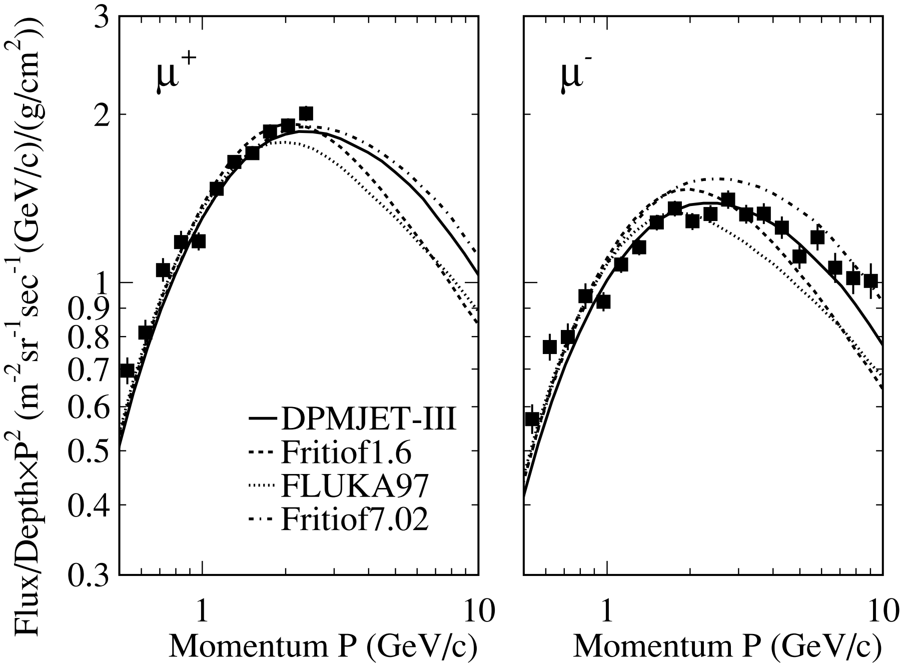

Fig 4. Observed and calculated [*Flux*/*Depth*] of muons at small atmospheric depth.

Fig. 3 shows the growth curve measurement. From top to bottom are the momentum in GeV/c: 1.0, 1.5, 2.5, 3.9, and 6.3 [19, 20, 21, 22]. Statistics in the measurement are too poor to discuss cosmic-ray interactions in the atmosphere. Although ascending speed of the balloon is much slower than space shuttle, it is not slow enough to measure muon growth curves with sufficient statistics. Dedicated muon balloon flights are highly desirable to improve the statistics in muon growth curve measurement.

3.3. Near the Top of the Atmosphere

During balloon floating period, a typical thickness of the residual air is 5 g/cm^2, which acts as a "thin" target producing atmospheric muons. Projectile cosmic-ray particle interacts with the target only once. Since muon production process is predominant over decay process at a balloon floating altitude, the measurement is sensitive to hadronic interaction models.

It is usually difficult to acquire sufficient statistics of atmospheric muons during balloon flights, due to small flux of muon at balloon altitudes and very limited observation time. The BESS-2001 flight, carried out at Ft. Sumner, New Mexico, USA, was an unique experiment in this sense [23]. The balloon reached at a normal floating altitude of 36 km at a residual atmospheric depth of 4.5 g/cm^2, then gradually lost its altitude. During the descending period, cosmic-ray data were collected at atmospheric depths at 4.5 g/cm^2 through 28 g/cm^2.

4. Hadronic Interaction Model

We calculated the muon flux under the same environmental condition as that of the BESS-2001 balloon experiment [24]. As a hadronic interaction model, four Monte Carlo simulation packages were tested, i.e., Fritiof 1.6[25] used in HKKM95 calculation[26], Fritiof 7.02[27], FLUKA 97[28] and DPMJET-III [29]. The secondary cosmic rays at the balloon altitude are approximately proportional to the atmospheric depth, thus the ratio $[Flux/Depth]$ is determined almost only by the absolute flux of primary cosmic rays and hadronic interaction. Fig. 4 shows $[Flux/Depth]$ both for calculation and observed dada. In comparison of the calculations with the data, no interaction model was strongly excluded by the χ^2 study. Among all the interaction models we studied here, however, the DPMJET-III gives the best agreement between calculation and observation [24]. Therefore, DPMJET-III was used in the following studies.

5. Comparison between Observed and Calculated Muon Spectra

In Fig. 1, the resultant spectra observed at Tsukuba and Mt. Norikura are compared with the expected spectra calculated with DPMJET-III, assuming the same observational conditions as the observations. In a higher momentum region than 30 GeV/c, calculated flux is about 10 % smaller than the observed one. Although the muon fluxes at ground level are affected by some factors other than the hadronic interactions, such as the atmospheric density structure, the disagreement might suggests more pions should be produced via hoadronic interactions.

Fig. 2 shows the comparison between observed and calculated atmospheric muon spectra in a lower momentum region. Those spectra show good agreement with each other. In a lower momentum region than 1 GeV/c, however, some disagreement was found between them. Irrespective of muon charge nor observation altitude, the calculation predicted about 10 % lower flux than observation.

6. Summary

Precise measurement of atmospheric muons must be very powerful tools to calibrate the calculations of atmospheric neutrinos. These measurement gives indispensable fundamental data to study neutrino oscillation phenomena using atmospheric neutrinos observed neutrino telescopes such as Super-Kamiokande.

Using the recent measurements of primary cosmic rays and DPMJET-III hadronic interaction package, we can well reproduce the observed atmospheric muon spectra. In the muon spectra below 1 GeV/c and above 30 GeV/c, however, there found 10 % deviation between calculation and observation. It suggests our calculation should be modified. Precise measurement of primary and atmospheric cosmic rays is essentially important to improve the accuracy of our prediction of atmospheric neutrinos.

Acknowledgments

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