# Calculation of Muon Fluxes at the Small Atmospheric Depths

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**Abstract**

Precise understanding of hadronic interaction between primary cosmic rays and atmospheric nuclei is very important and fundamental to study atmospheric neutrinos and their oscillations. We studied hadronic interaction models using the data of primary and secondary cosmic rays observed by BESS experiments. In the comparison of the observed spectra to the calculated ones by using some interaction models, DPMJET-III is the most favored among all the interaction models we studied here.

## 1. Introduction

The discovery of neutrino oscillations and its finite mass using the atmospheric neutrino is a mile stone in the history of particle physics. Next step would be the accurate determination of the oscillation parameters. However, the capability of neutrino experiments using the atmospheric neutrinos is limited by the accuracy of the predicted neutrino fluxes. The main uncertainties in the calculation of the atmospheric neutrino flux are the uncertainties of primary cosmic-ray flux and hadronic interactions. We note that the uncertainty of the cosmic-ray proton fluxes is remarkably reduced by the recent cosmic ray observations up to 100 GeV. For the hadronic interactions, however, there were almost no recent experiments available for our purpose.

In this paper, we study the interaction model using the data of primary and secondary cosmic rays observed by the BESS experiment simultaneously at the balloon altitude. The muons at the balloon altitude are considered to carry direct informations of the hadronic interaction of primary cosmic rays and air nuclei. However, it is usually difficult to acquire sufficient statistics during balloon experiments, due to the small flux of muons at the balloon altitude. The BESS-2001 flight is unique and interesting in this sense. During the flight, the balloon kept a relatively lower altitude, corresponding to the air depth of 4.5 - 28 g/cm$^2$ for a long time, and registered a sufficient number

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of muons. The result of this study is applied to the new calculation of atmospheric neutrinos, which is also presented in this conference.

## 2. BESS Experiments

The BESS (Balloon-borne Experiment with a Superconducting Spectrometer) detector [2,3,8,13,14] is a high-resolution spectrometer with a large acceptance to perform precise measurement of absolute fluxes of various primary cosmic rays, as well as highly sensitive searches for rare cosmic-ray components. In the previous measurements, BESS obtained precise atmospheric muon spectra at sea level [6] and mountain altitudes [12] as well as precise primary proton and helium spectra [11].

The BESS-2001 balloon flight was carried out at Ft. Sumner, New Mexico, USA (34°49′N, 104°22′W) on 24th September 2001. Throughout the flight, the vertical geomagnetic cut-off rigidity was about 4.2 GV. Fig. 1 shows a balloon flight profile during the experiment. The balloon reached at a normal floating altitude of 36 km at an 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 between 4.5 g/cm$^2$ and 28 g/cm$^2$.

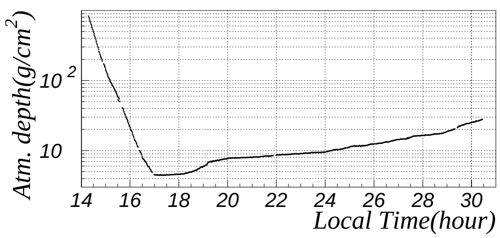


**Fig. 1.** Atmospheric depths during the BESS-2001 balloon flight experiment.

The proton and helium fluxes in energy ranges of 0.5–10 GeV/n and muon flux in 0.5 GeV/*c*–10 GeV/*c* were obtained [1]. The overall errors including both statistic

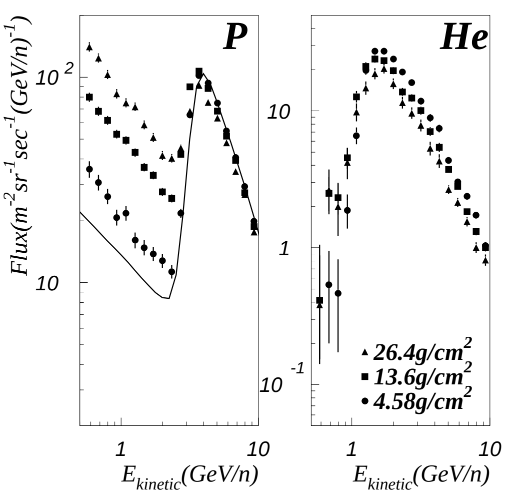


**Fig. 2.** The observed proton and helium spectra. Solid line in the left figure is the calculated proton flux for 4.58 g/cm$^2$

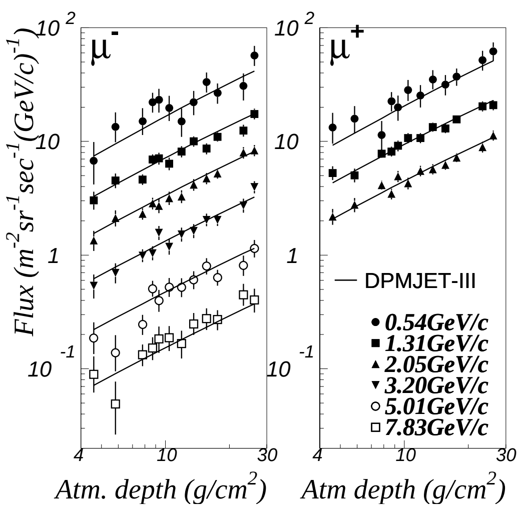


**Fig. 3.** The observed negative and positive muon fluxes as a function of atm. depth.

and systematic errors are less than 8 %, 10% and 20 % for protons, helium nuclei and muons, respectively. The obtained proton and helium spectra are shown in Fig. 2. Fig. 3 show the observed muon flux together with the predicted ones [10] as a function the residual atmospheric depth. For understanding of the interactions and tuning the models in the calculation, these data are essentially important to be compared with the calculation.

## 3. Comparison of data and calculation.

We calculated the muon flux same environmental condition as that of the BESS-2001 balloon experiment, with several interaction models. The primary flux model used here is essentially the one reported in Gaisser et al. [5] with modulation function so that it reproduce the proton cosmic ray flux observed at 4.58 $\mathrm{g/cm^2}$ at the energies above the rigidity cut-off of 4.2GV. The proton flux at 4.58 $\mathrm{g/cm^2}$ calculated in this procedure is plotted in Fig. 2.

We plot the quantity (muon flux)/depth for observed data in Fig. 4. For the calculated flux, we depict the same quantity only for 4.58, 13.6 26.4 $g/cm^2$ in the same figure for DPMJET-III [10] and Fritiof 1.6 [7] (used in HKKM95) interaction models. The curves for all atmospheric depths are very close. It

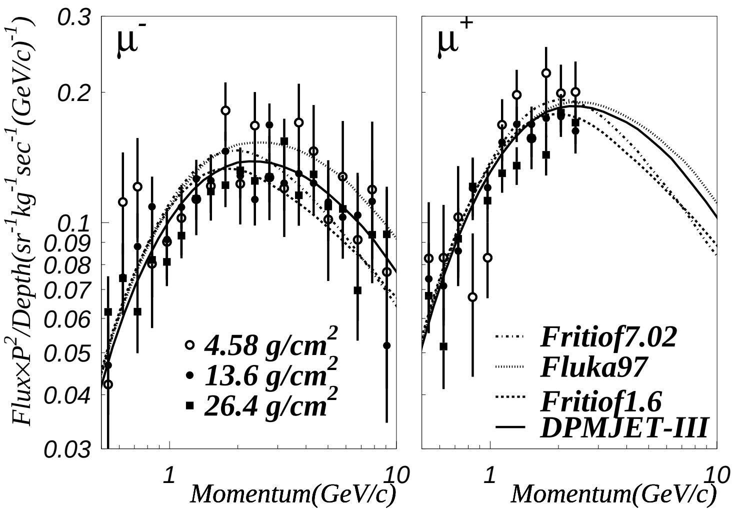


**Fig. 4.** The observed in BESS-2001 and calculated (muon flux)/(atm. depth).

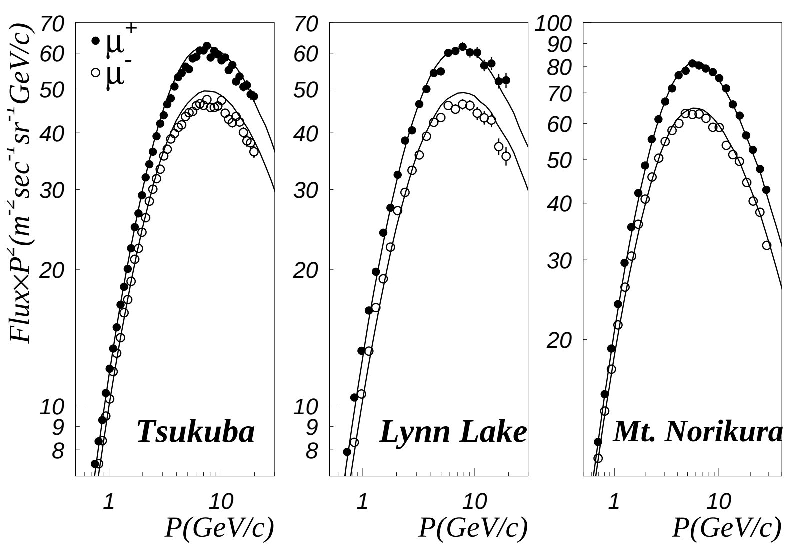


**Fig. 5.** The observed and calculated muon spectra at Tsukuba, Lynn Lake and Mt. Norikura.

is clearly seen from these figures that the agreement of data and calculation is better for DPMJET-III. Quantitatively, the $\chi^2$ is 1.61 for DPMJET-III and 2.14 for Fritiof 1.6. We have made the same analysis for FLUKA 97 [4] and Fritiof 7.02 [9], and the $\chi^2$ are 1.77 and 2.14 respectively. In Figs. 5, we plotted the ground level muon flux observed at Lynn lake, Mt. Norikura, and Tsukuba. Also plotted are the muon flux calculated by DPMJET-III. The muon fluxes at ground level are also affected by the variation atmospheric density structure, and procedure of the particle propagation in the air. However, we can see that the agreements of data and calculations are reasonably good.

In the comparison of data and calculated fluxes by the interaction models, no interaction model is strongly excluded by the $\chi^2$ study. Among all the interaction models we studied here, However, DPMJET-III is the most favored.

## 4. Summary

Using the primary and secondary cosmic-ray fluxes measured by the BESS-2001 experiment, we study the interaction model used in the atmospheric neutrino calculation. The BESS-2001 flight carried out at Ft. Sumner, New Mexico, provided a very unique opportunity to measure precise cosmic-ray fluxes at small atmospheric depths of 4.5 g/cm$^2$ through 28 g/cm$^2$. We calculated muon fluxes with some interaction models and compared with the obtained fluxes. The same simulation program simultaneously calculates the atmospheric neutrinos. Four interaction models were used to calculate the muon flux. As a result of $\chi^2$ study, no interaction model was strongly excluded, however, DPMJET-III is the most favored in all the interaction models we studied here. It reproduced atmospheric muons observed at sea level (Tsukuba, Lynn Lake) and mountain altitude (Mt. Norikura).

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