
Calculation of Muon Fluxes at the Small Atmospheric Depths

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Abstract

Precise knowledge of the 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. By comparing the observed spectra with the ones calculated by several interaction models, we found DPMJET-III is most favored among them.

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. The 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 uncertainty in the calculation of the atmospheric neutrino flux stems from 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 are scarcely any recent experiments available for our purpose.

In this paper, we study interaction models using the data of primary and secondary cosmic rays observed simultaneously by the BESS experiment at balloon altitudes. Muons at balloon altitudes are considered to carry direct informations of the hadronic interaction of primary cosmic rays with air nuclei. However, it is usually difficult to acquire sufficient statistics during balloon flights, due to small muon fluxes at balloon altitudes. The BESS-2001 flight is unique and interesting in this sense. During the flight, the balloon kept relatively lower altitudes, corresponding to the air depths of 4.5 - 28 g/cm² for a long time, and registered a

sufficient number of muons. The result of this study is applied to a new calculation of atmospheric neutrinos, which is also presented in this conference [6].

2. BESS Experiments

The BESS (Balloon-borne Experiment with a Superconducting Spectrometer) detector [2,3,9,14,15] 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 [7] and mountain altitudes [13] as well as precise primary proton and helium spectra [12].

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. Figure 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/cm², then gradually lost its altitude. During the descending period, cosmic-ray data were collected at atmospheric depths between 4.5 g/cm² and 28 g/cm².

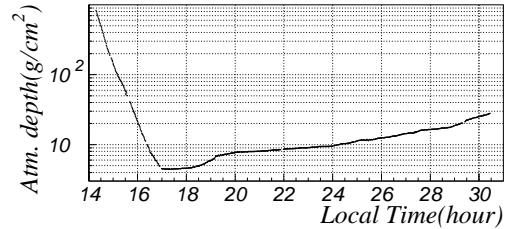


Fig. 1. Atmospheric depths during the BESS-2001 flight.

The proton and helium fluxes in the energy range 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 and systematic errors are less than 8 %, 10% and 20 % for protons,

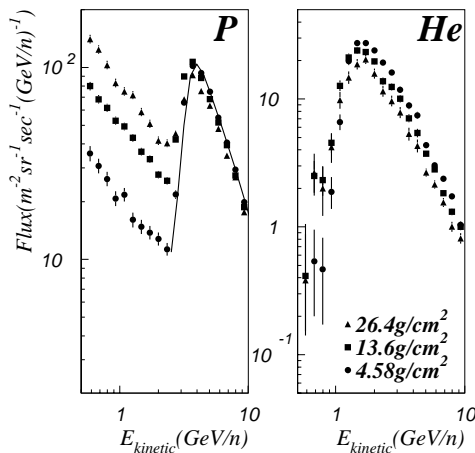


Fig. 2. The observed proton and helium spectra. Solid line shows the calculated proton fluxes at 4.58 g/cm².

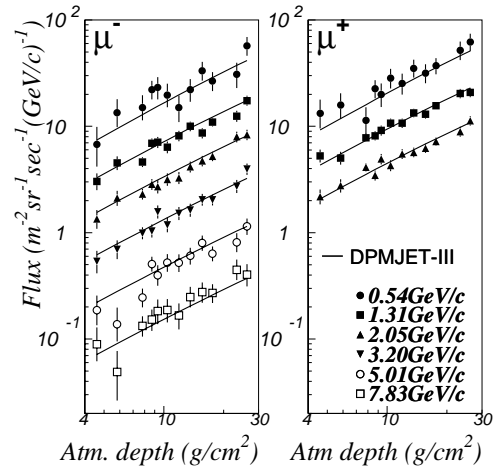


Fig. 3. The observed negative and positive muon fluxes as a function of atm. depth.

helium nuclei and muons, respectively. The obtained proton and helium spectra are shown in Fig. 2. Figure 3 shows the observed muon flux together with the predicted ones [11] as a function of the residual atmospheric depth. For understanding the interactions and tuning the models in the calculation, these data are essentially important to be compared with calculations.

3. Comparison of the data with calculation.

We calculated the muon flux under the 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 a modulation function so that it reproduce the proton cosmic ray flux observed at 4.58 g/cm² at the energies above the rigidity cut-off of 4.2 GV. The proton flux at 4.58 g/cm² 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/cm² in the same figure for DPMJET-III [11] and Fritiof 1.6 [8] (used in

HKKM95) interaction models. The curves for all atmospheric depths are very close. It is clearly seen from these figures that the agreement between the data and calculation is better for DPMJET-III. Quantitatively, the χ^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

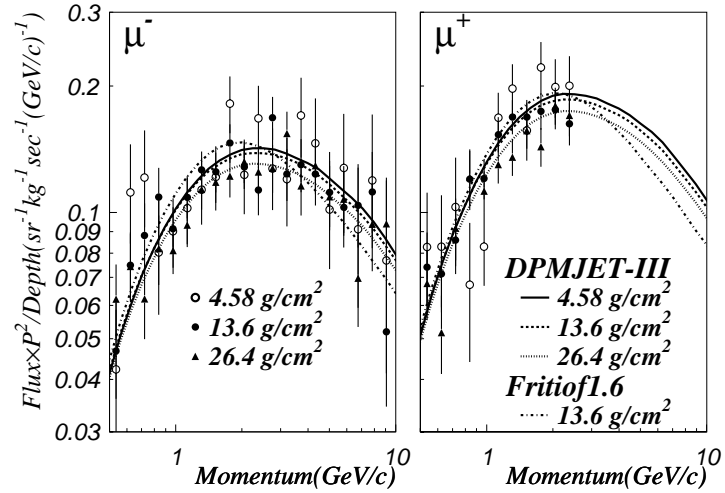


Fig. 4. The observed and calculated (muon flux)/(atm. depth in kg/m²).

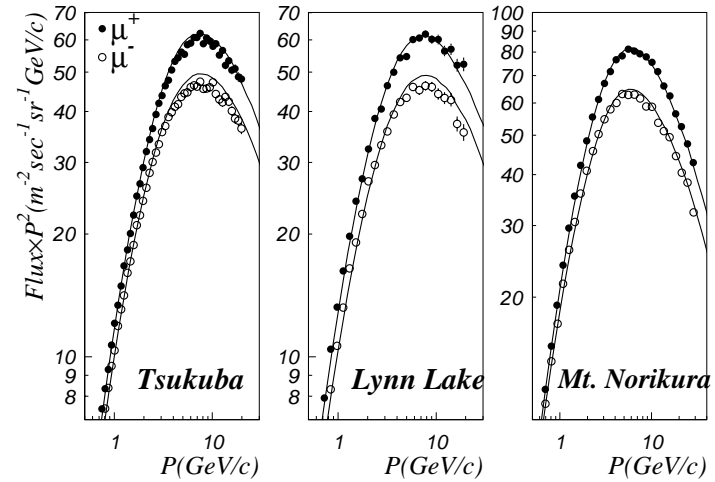


Fig. 5. The observed and calculated muon spectra at Tsukuba, Lynn Lake and Mt. Norikura.

Fritiof 7.02 [10], and the χ^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 affected by the atmospheric density structure, and procedures other than the hadronic interactions. However, we can see that the agreements of data and calculations are reasonably good.

In the comparison of data with calculated fluxes of the several interaction models, no interaction model is strongly excluded by the χ^2 study. Among all the interaction models we studied here, however, DPMJET-III is the most favored.

4. Summary

The BESS-2001 flight provided a very unique opportunity to measure precise cosmic-ray fluxes at small atmospheric depths of 4.5 g/cm² through 28 g/cm². Using the primary and secondary cosmic-ray fluxes measured by the BESS-2001 experiment, we studied four interaction models used in the atmospheric neutrino calculations. As a result of χ^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 and Lynn Lake) and mountain altitude (Mt. Norikura).

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