Available online at www.sciencedirect.com
SCIENCE DIRECT®
Nuclear Physics B (Proc. Suppl.) 145 (2005) 132–135
NUCLEAR PHYSICS B
PROCEEDINGS SUPPLEMENTS
www.elsevierphysics.com

Measurement of cosmic-ray spectra with the BESS/BESS-TeV

T. Sanuki[a] for the BESS Collaboration

[a]The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

In order to study neutrino oscillation phenomena using atmospheric neutrinos, it is crucially important to calculate their absolute fluxes and spectral shapes accurately. Absolute flux of primary cosmic ray is the most fundamental information for the calculation. Since production and decay processes of muons are accompanied by neutrino production, observation of atmospheric muons gives fundamental information about atmospheric neutrinos. Our measurement of primary and atmopspheric cosmic rays at various sites with the BESS/BESS-TeV spectrometer will help to improve the accuracy of atmospheric neutrino calculations.

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}) is expressed as

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

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 $Y_{p(A)\to\nu_i}$.

2. Atmospheric Neutrino Calculation

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

$$p/A + \mathrm{Air} \to \pi + \pi + \cdots, \quad (2)$$

$$\pi \to \mu + \nu_\mu, \quad (3)$$

$$\mu \to e + \nu_e + \nu_\mu. \quad (4)$$

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 [3–5]. 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. It seems reasonable to suppose that we already know the $\phi_{p(A)}$ up tp around 100 GeV and $R_{p(A)}$ in Eq. (1) with sufficient accuracy.

In contrast with a long-baseline experiment, such as K2K [7], the feature of the oscillation study with atmospheric neutrinos lies in its wide energy range. For example, the Super Kamiokande water Cherenkov detector [8] can observe neutrinos from 0.1 to 100 GeV. In order

0920-5632/$ – see front matter
doi:10.1016/j.nuclphysbps.2005.03.051

to estimate an accurate flux of atmospheric neutrinos up to around 100 GeV, we need to know the primary cosmic-ray flux well above 100 GeV and the feature of hadronic interactions in that energy region. It is crucial to measure primary cosmic-ray flux by determining the absolute energy of particles. Measurements of atmospheric muon spectrum is also important to check and improve our understanding of hadronic interactions.

3. BESS-TeV spectrometer

The BESS spectrometer was upgraded, as shown Figure 1, to be equipped with new tracking detectors so as to improve its resolution in momentum measurement. The upgraded spectrometer, BESS-TeV, records up to 60 hit points along a track, whose length is as long as 1.6 m. Each hit point was measured with a spacial resolution of 150 μm [9].

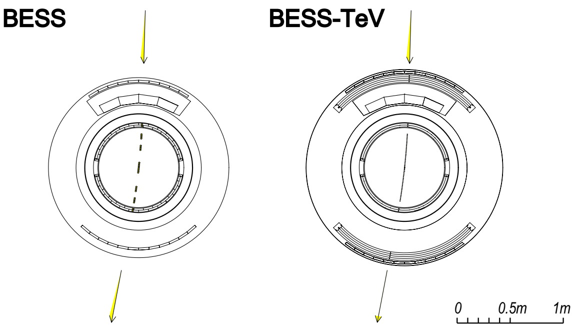

Figure 1. Schematic cross-sectional views of BESS and BESS-TeV spectrometer.

Fig. 2 shows a distribution of the deflection resolution (ΔR^{-1}) obtained with all the drift chambers. The deflection resolution was evaluated in the track-fitting procedure for cosmic-ray protons. Those of other spectrometers used in previous balloon experiments [5,10,11] are also shown. Each area of the histogram is normalized to unity. The peak position of 0.7 TV^{-1} corresponds to the MDR of 1.4 TV.

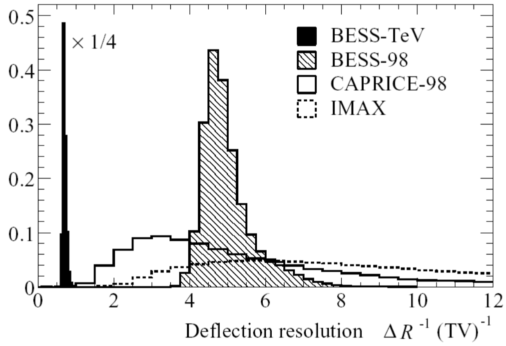

Figure 2. Distribution of the deflection resolution.

4. OBSERVATION

4.1. Primary cosmic ray

The BESS-TeV spectrometer succeeded in measuring primary proton and helium spectra up to 540 GeV and 250 GeV/n, respectively [9]. The primary cosmic rays in this energy range are relevant to atmospheric neutrinos observed as "contained events" in Super-Kamiokande. Thus it is reasonably supposed that the resultant spectra provide the $\phi_{p(A)}$ and $R_{p(A)}$ in Eq. (1) with sufficient accuracy for estimating an event rate of "contained events."

4.2. Atmospheric muon

4.2.1. BESS-2001 Observation

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. During balloon ascending period, we can observe a growth curve of atmospheric muons, which is a correlation between muon intensity and a thickness of the resid-

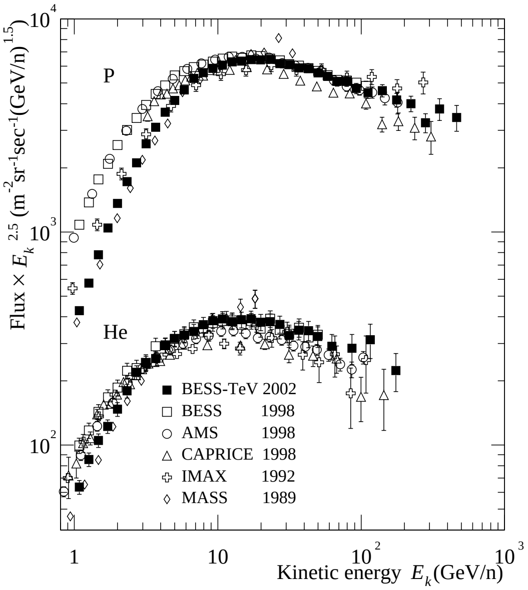

Figure 3. Absolute differential energy spectra of primary protons and helium nuclei.

ual atmosphere. Since the production and decay process of muons are accompanied by neutrino production as shown in Eqs. (2) – (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.

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 [12]. 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.

4.2.2. Hadronic interaction model

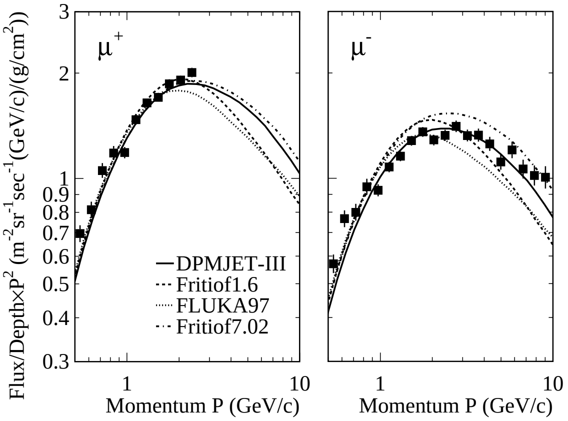

Figure 4. Observed and calculated $[Flux/Depth]$ of muons at small atmospheric depth.

We calculated the muon flux under the same environmental condition as that of the BESS-2001 balloon experiment [13]. As a hadronic interaction model, four Monte Carlo simulation packages were tested, i.e., Fritiof 1.6[14] used in HKKM95 calculation[15], Fritiof 7.02[16], FLUKA 97[17] and DPMJET-III [18]. Figure 4 shows $[Flux/Depth]$ both for calculation and observed dada. Among all the interaction models we studied here, the DPMJET-III gives the best agreement between calculation and observation [13].

4.2.3. Cosmic-ray spectra on the ground

Figure 5 shows atmospheric muon spectra observed with the BESS/BESS-TeV spectrometer at Tsukuba and Mt. Norikura, Japan,[19, 20] together with the prediction calculated with DPMJET-III. Atmospheric muon spectrum in a higher momentum range is shown in Figure 6 [9]. Observed and calculated spectra show good agreement with each other between 1 GeV/c and 30 GeV/c. Although the muon fluxes at ground level are affected by some factors other

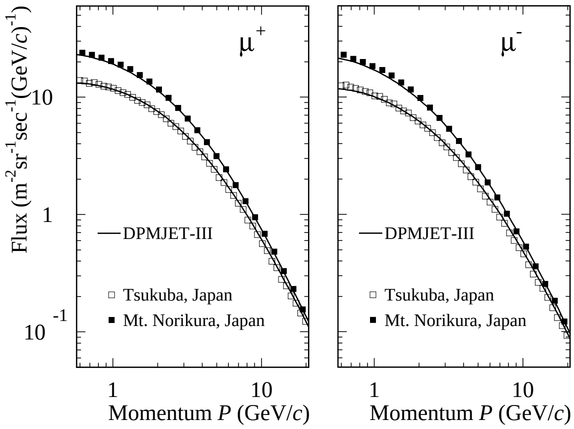

Figure 5. Observed and calculated spectra of atmospheric muon in a lower momentum region.

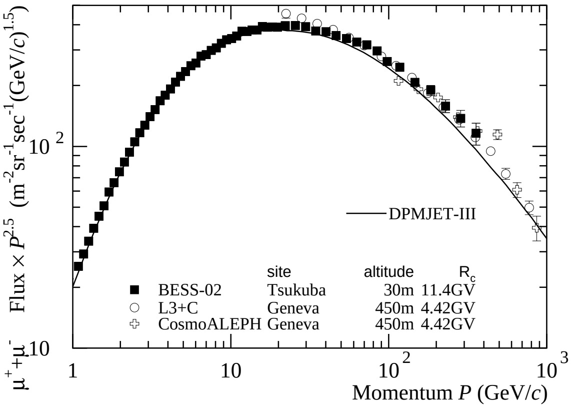

Figure 6. Observed and calculated spectra of atmospheric muon in a higher momentum region.

than the hadronic interactions, such as the atmospheric density structure, the disagreement might suggests more pions should be produced via hoadronic interactions.

5. SUMMARY

We have measured primary and atmospheric cosmic rays at various sites with the BESS and BESS-TeV spectrometers. These spectra will help to improve the calculation of atmospheric neutrinos.

Acknowledgments

The author deeply thank Doctor M. Honda for his calculations of atmospheric cosmic-ray particles. The BESS experiment was supported by Grant-in-Aid for Scientific Research (12047206 and 12047227) from the Ministry of Education, Culture, Sport, Science and Technology, Japan.

REFERENCES

1. Y. Fukuda et al., Phys. Rev. Lett. 81 (1998) 1562.
2. See, for example, T. K. Gaisser, Proc. Neutrino Oscillations and their Origin, ed. Y. Suzuki, M. Nakahara, N.Shiozawa, and K. Kaneyuki (Tokyo, UAP Inc.), 45 (2000).
3. J. Alcaraz et al., Phys. Lett. B 490 (2000)27.
4. J. Alcaraz et al., Phys. Lett. B 494 (2000)193.
5. T. Sanuki et al. ApJ 545 (2000) 1135.
6. J. Alcaraz et al., Phys. Lett. B 472 (2000) 215.
7. M.H. Ahn et al., Phys. Rev. Lett. 90 (2003) 041801.
8. S. Fukuda et al., NIM A 501 (2003) 418.
9. S. Haino et al., Phys. Lett. B 594 (2004) 35.
10. M. Boezio et al., Astropart. Phys. 19 (2003) 583.
11. W. Menn et al., ApJ 533 (2000) 281.
12. K. Abe et al., Phys. Lett. B 564 (2003) 8.
13. K. Abe et al., Proc. 28th ICRC 3 (2003) 1463, astro-ph/0312632.
14. B. Nilsson-Almqvist et al., Comp. Phys. Comm. 43 (1987) 387.
15. M. Honda et al, Phys. Rev. D54 (1995) 4985.
16. H. Pi et al., Comp. Phys. Comm. 71 (1987) 173.
17. G. Battistoni et al, astro-ph/0207035.
18. S. Roeseler et al., hep-ph/0012252.
19. T. Sanuki et al., Phys. Lett. B 541 (2002) 234.
20. M. Motoki et al., Astropart. Phys. 19 (2003) 113.