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Precise Measurement of Atmospheric Muon Fluxes at Sea Level

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Abstract. The vertical absolute fluxes of atmospheric muons and the muon charge ratio have been measured precisely at different geomagnetic locations by using the BESS spectrometer. The observations have been performed at 30 m above sea level in Tsukuba, Japan, and at 360 m above sea level in Lynn Lake, Canada. The vertical cutoff rigidities in Tsukuba ($36.2°N$,$140.1°E$) and in Lynn Lake ($56.5°N$,$101.0°W$) are 11.4 GV and 0.4 GV, respectively. We have obtained vertical fluxes of positive and negative muons in a momentum range of 0.6 to 20 GeV/c with an estimated systematic error of 2.4 % for positive muons and 2.2 % for negative muons in Tsukuba and 2.2 % for positive muons and 1.9 % for negative muons in Lynn Lake. By comparing the data collected at two different geomagnetic latitudes, we have seen an effect of cutoff rigidity. Those precise measurements of the muon fluxes at sea level are important to understand the cosmic-ray interactions inside the atmosphere and to evaluate the parameters of atmospheric neutrino oscillation.

1 Introduction

The evidence for atmospheric neutrino oscillation has been presented by the Super-Kamiokande collaboration by using the high-statistical samples of neutrino interaction (Fukuda *et al.* , 1998). Primary cosmic-ray particles, mainly consisting of protons and helium nuclei, interact with atmospheric nuclei and produce secondary pions and kaons. In evaluating flux of muon neutrino, a dominant systematic error arises from the uncertainty in the flux of primary cosmic-rays and the production cross section of secondary mesons (Gaisser *et al.* , 1996). Since muon and muon neutrino are always produced in pairs and the kinematics of meson decay is well known, the measurement of atmospheric muon is crucial to verify the estimation of neutrino flux. There still remains an uncertainty due to kaon production. Kaons decay into muons directly or through various hadronic decay modes and the muon energy spectrum is different from the $\pi - \mu$ decay. The difference increases with muon energy because of larger Q value for the $K - \mu$ decay. However, $\pi - \mu$ decay contribution for muons is dominant process, this contribution is about 90 % below 10 GeV/c and still larger than 80 % at 100 GeV/c for vertical direction. Neutrinos created by $\pi - \mu$ decay are major component below 30 GeV/c for vertical direction (Honda *et al.* , 1995). Therefore the precise measurement of the atmospheric muon flux will reduce the systematic error due to the primary cosmic-ray flux, particle interactions and atmospheric models.

The muon flux at sea level has been measured by many groups. However, there are large discrepancies between experiments compared with the statisitical errors quoted in each publication. Therefore it is conceivable that the differences come from systematic effects such as uncertainties in the determination of particle momentum, geometrical factor, exposure time, particle identification, trigger efficiency and normalization data obtained by absolute integral flux. To minimize these systematic errors are crucial.

We report here a precise measurement of the absolute flux of atmospheric muons at sea level in Japan (Tsukuba, '95, cutoff rigidities of 11.2 GV) and in northern Canada (Lynn Lake, '97, '98 and '99, cutoff rigidities of 0.5 GV) by using thin walled material spectrometer of BESS (Ajima *et al.* , 2000). The sprctrometer has many tracking points in the strong magnetic field, hence it can measure momentum precisely. The instruments can measure muon flux with small systematic errors, because we can visualize all the events that pass through the spectrometer. BESS spectrometer is also used to measure primary cosmic-ray flux, protons and helium nuclei (Sanuki *et al.* , 2000), hence the systematic accuracy of atmospheric neutrino calculation will be improved by using these fluxes together with present results.

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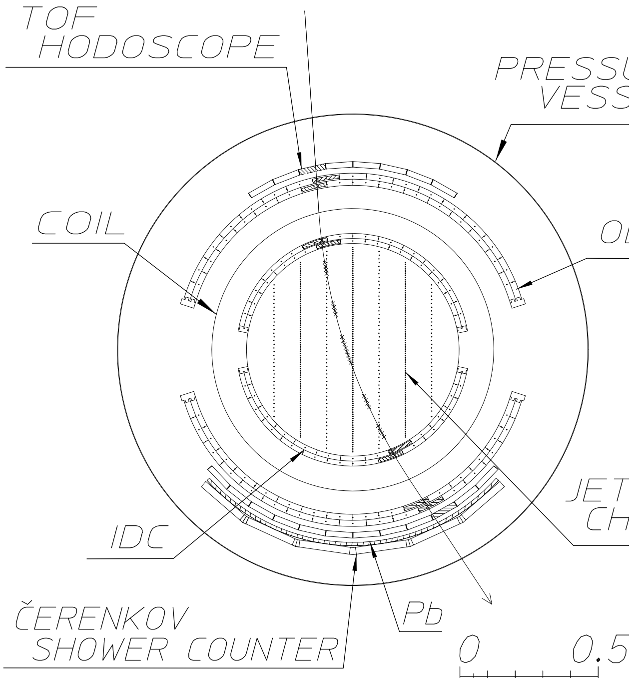

Fig. 1. Cross-sectional view of the BESS '95 detector.

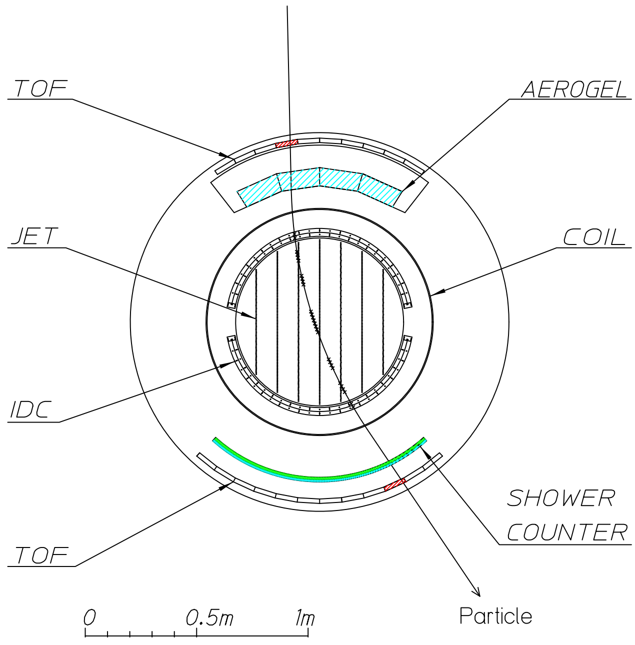

Fig. 2. Cross-sectional view of the BESS '99 detector.

2 BESS detector

The BESS detector was designed as a high resolution spectrometer with a large acceptance to perform precise measurements of primary and secondary cosmic-rays as well as a sensitive search for rare exotic particles (Orito , 1987; Yamamoto *et al.* , 1994). A cross-sectional view of '95 and '99 configurations are shown in Fig. 1 and Fig.2 respectively. The detector configuration was slightly different in each experiment. '97 and '98 configuration were similar to '99 configuration except with shower counters in '99 configuration.

First, we outline the '95 configuration. The thin superconducting coil (Yamamoto *et al.* , 1988) (4.70 g/cm^2 thick including the cryostat) produces a uniform axial magnetic field of 1 Tesla. A jet-type drift chamber (JET), inner drift chambers (IDCs) and outer drift chambers (ODCs) are located inside and outside the coil. These chambers are filled with a slow gas (CO_2 90 %, Ar 10 %). Tracking point of drift chambers are read out by flash ADCs. The $r\phi$-tracking is performed by fitting up to 28 hit-points, each with 200 μm resolution. Tracking in the z-coordinate is made by fitting points in IDC measured with vernier pads with an accuracy of 470 μm and points in the JET chamber measured using charge-division with 20 mm resolution. By using these data, we performed the continuous and redundant 3-dimensional track information. In order to get transverse momentum of particle, we used 28 hit-points of the JET chamber and IDCs. The ODCs provide extra hit positions outside the magnet and is used to calibrate the JET chamber and IDCs. In addition, all drift chambers have capability to see the multi-hit. This feature enables us to recognize multi-track events, thus we could see the tracks having interactions and scatterings. The time-of-flight (TOF) scintillator hodoscopes measured the TOF of particles with resolution of 110 ps in '95. Acrylic Čerenkov shower counter consists of acrylic and lead plate (12 mm). These counters are placed outside the lower TOF counter. Acrylic Čerenkov shower counters, used to separate electron and muons, were installed for the ground observation. The total material thickness from outside the pressure vessel, passing through superconducting magnet coil, inside the JET chamber was 9.03 g/cm^2.

Since '97 experiment, we installed a newly developed threshold-type Cherenkov counter with silica-aerogel radiator, instead of ODCs (Asaoka *et al.* , 1998). The resolution of TOF was improved to 75 ps by using PMTs with larger diameter for better light collection (Shikaze *et al.* , 2000). In '99 experiment, we installed shower counters just below superconducting magnet.

The '95 ground experiment was carried out at KEK, Tsukuba ($36.2°N$,$140.1°E$), Japan, from December 23 to 28. KEK is located at 30 m above sea level. The vertical cutoff rigidity is 11.2 GV ($\lambda = 26.6°N$ of geomagnetic latitude (World Data Center for Geomagnetism , Web site)). The mean atmospheric pressure in this experiment was 1010 hPa (1030 g/cm^2). The scientific data were taken for a period of 291,430 sec of live time and 9,148,104 events were recorded on magnetic tapes. The '97, '98 and '99 ground experiments were carried out in Lynn Lake ($56.5°N$, $101.0°W$), Canada, on July 22, August 16 and July 26, respectively. The experimental site in LynnLake is located at 360 m above sea level. The vertical cutoff rigidity is 0.5 GV ($\lambda = 65.5°N$ of geomagnetic latitude (World Data Center for Geomagnetism , Web site)). The mean atmospheric pressures in Lynn Lake experiments in '97, '98 and '99 was 980.6 hPa (1000 g/cm^2),

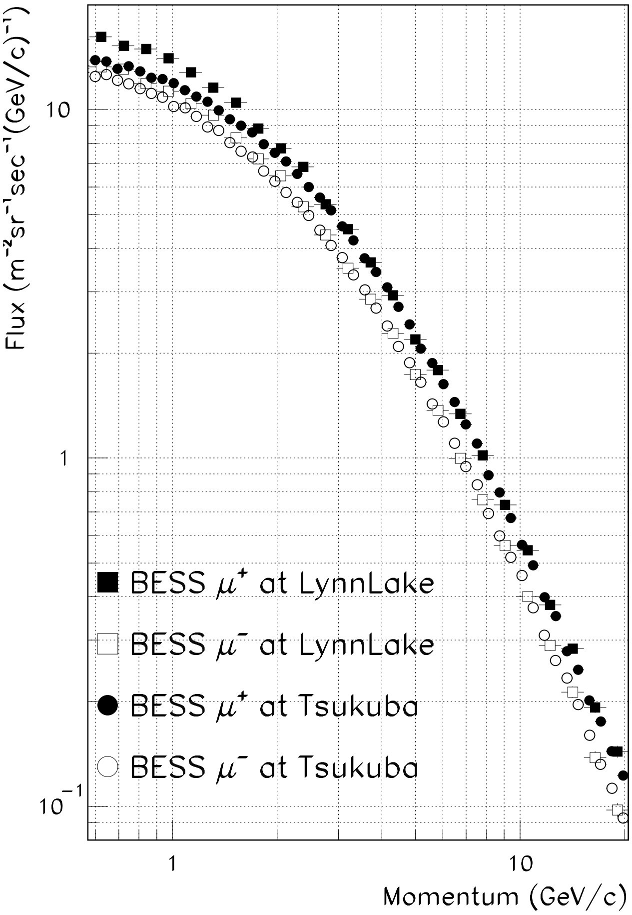

Fig. 3. BESS results of vertical differential momentum spectrum of positive and negative muons at sea level .

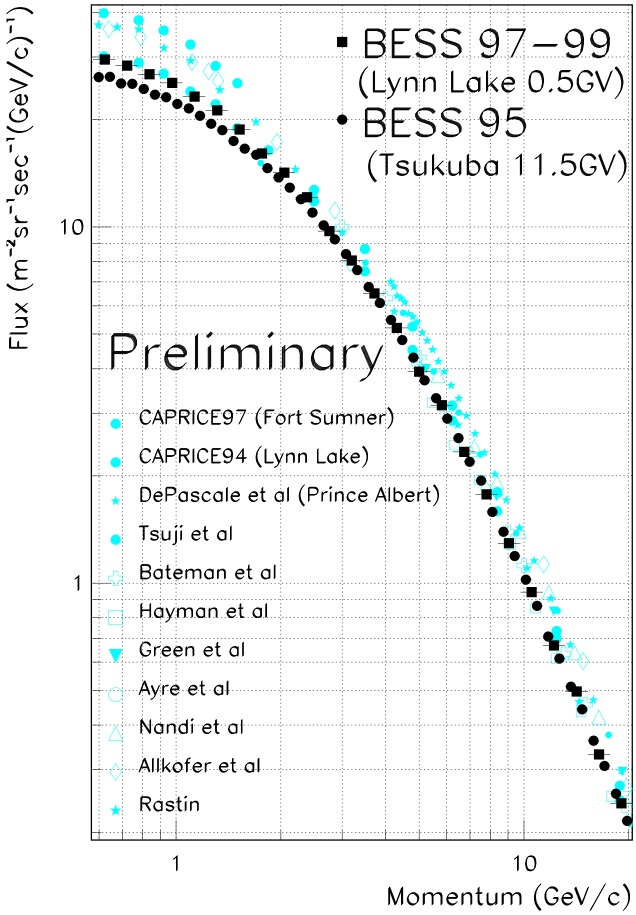

Fig. 4. BESS results of vertical differential momentum spectrum of muons at sea level together with previous data.

990.5 hPa (1010 g/cm^2) and 964.9 hPa (983.9 g/cm^2), respectively. The total scientific data were obtained for a period of 21,304 sec (7,011 sec, 3,949 sec and 10,344 sec) of live time and 242,934, 137,629 and 354,869 events were recorded on magnetic tapes, respectively.

The trigger was provided by a coincidence between the top and the bottom scintillators of TOF counters. All triggered events were gathered in magnetic tape. In order to analyze the experimental data, we made data summary tape (DST). The core information (momentum, T.O.F., etc.) was composed and extracted from original data.

3 Result

Fig. 3 shows the resultant positive and negative muon fluxes. We have obseved vertical flux of positive and negative muons in the momentum range from 0.6 to 20 GeV/c with an estimated systematic error of 2.4 % for positive muons and 2.2 % for negative muons in Tsukuba and 2.2 % for positive muons and 1.9 % for negative muons in Lynn Lake. The vertical cutoff rigidities in Tsukuba ($36.2°N$,$140.1°E$) and in Lynn Lake ($56.5°N$,$101.0°W$) are 11.2 GV and 0.5 GV, respectively. By comparing the data collected at two different geomagnetic latitudes, we have observed an effect of cutoff rigidity.

Fig. 4 shows the total differential muon spectrum together with the measurements at Lynn Lake and previous measurements (Hayman *et al.* , 1962; Green *et al.* , 1979; Ayre *et al.* , 1975; Nandi *et al.* , 1972; Allkofer *et al.* , 1971; Bateman *et al.* , 1971; Rastin , 1984; Tsuji *et al.* , 1998; DePascale *et al.* , 1993; Kremer *et al.* , 1999). Our data on the muon flux that were multiplied by p^2 at sea level are shown in Fig. 5. From these figures, it was obvious that the muon flux measured in Tsukuba and in Lynn Lake were different in lower momentum ranged below 3.5 GeV/c, but were in good agreement in momentum ranged beyond 3.5 GeV/c. This is because cutoff rigidity for primary cosmic-rays does not affect in higher momentum.

Fig. 6 shows the charge ratio of muons together with previous measurements (Kremer *et al.* , 1999; Appleton *et al.* , 1971; Baxendale *et al.* , 1975; Nandi *et al.* , 1972; Rastin , 1984). It was seen that the charge ratio obtained in Tsukuba decreased below 3.5 GeV/c while the charge ratio obtained in Lynn Lake remained constant value. This deviation comes from the influence of the geomagnetic cut off rigidity. Many of systematic error were canceled by calculating this ratio.

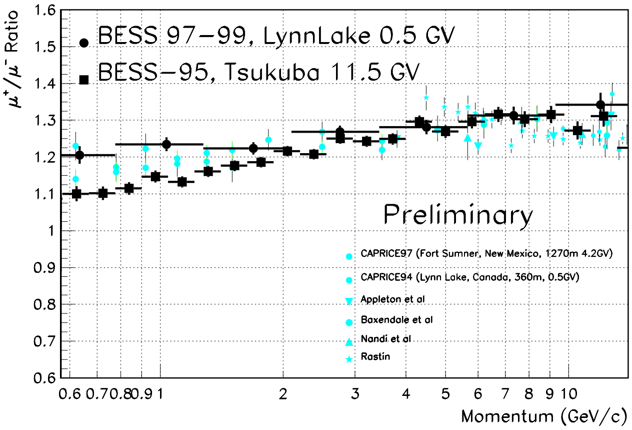

Fig. 6. BESS results of muon charge ratio at sea level together with previous data.

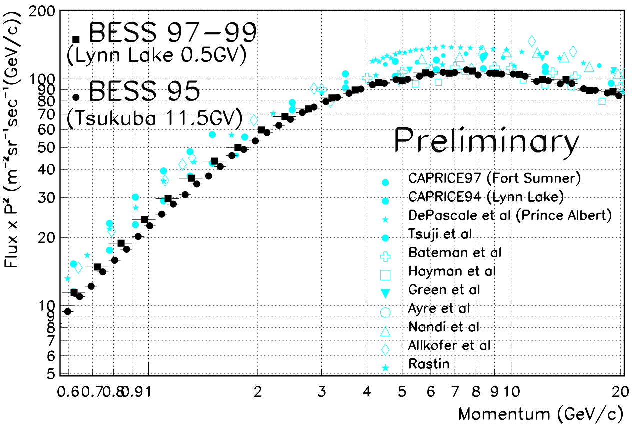

Fig. 5. BESS results of vertical differential momentum spectrum of muons multiplied by p^2 at sea level together with previous data.

Muon charge ratio observed in Tsukuba had systematic errors of proton subtraction and east-west effect. On the other hand, muon charge ratio observed in Lynn Lake had systematic errors due to only proton subtraction.

4 Conclusion

We observed atmospheric muon fluxes precisely. The obtained momentum spectrum appeared to be good agreement with recent CAPRICE 94 (Kremer *et al.* , 1999) data. These data agreed within the systematic and statistic errors. But previous experiments were about 20 % larger than these recent experiment. It was considered that systematic error of absolute flux is main component of these difference. But these fluxes agreed well when we compared with shape of these spectrum. Our result with a little systematic error is very important because of this reason.

We observed the geomagnetic effect by comparing the muon fluxes observed at Tsukuba, Japan and Lynn Lake, Canada. Muon charge ratio obtained at these two site also showed geomagnetic effect.

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