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Atmospheric muons at various altitudes

T. Sanuki[1], Y. Yamamoto[1], M. Motoki[1,†], K. Abe[1], K. Anraku[1], Y. Asaoka[1], M. Fujikawa[1], H. Fuke[1], M. Imori[1], S. Haino[1], K. Izumi[1], T. Maeno[2], Y. Makida[3], N. Matsui[1], H. Matsumoto[1], H. Matsunaga[1,‡], J. Mitchell[4], T. Mitsui[2,†], A. Moiseev[4], J. Nishimura[1], M. Nozaki[2], S. Orito[1,*], J. F. Ormes[4], T. Saeki[1], M. Sasaki[3], Y. Shikaze[1], E. S. Seo[5], T. Sonoda[1], R. Streitmatter[4], J. Suzuki[3], K. Tanaka[3], K. Tanizaki[2], I. Ueda[1], J. Z. Wang[5], Y. Yajima[6], Y. Yamagami[6], A. Yamamoto[3], K. Yamato[2], T. Yoshida[3], and K. Yoshimura[1]

[1]The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
[2]Kobe University, Kobe, Hyogo, 657-8501 Japan
[3]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
[4]National Aeronautics and Space Administration, Goddard Space Flight Center (NASA/GSFC), Greenbelt, MD 20771, USA
[5]University of Maryland, College Park, MD 20742, USA
[6]The Institute of Space and Astronautical Science (ISAS), Sagamihara, Kanagawa 229-8510, Japan

Abstract. We have carried out a series of atmospheric muon measurements with the BESS spectrometer at various altitudes.

At the top of Mt. Norikura, Japan (2,770 m above sea level, cutoff rigidity is 11.5 GV), muons at the mountain altitude were measured very precisely. The observed intensity of atmospheric muons is about 70 % higher than at sea level. During the ascending and floating periods of the balloon experiments, the intensity of atmospheric muons was also continuously measured. The muon energy spectra at float altitude (5 $\mathrm{g/cm^2}$) can provide much useful information about the hadronic interaction models. The measurement of muon growth curve in the atmosphere has been crucially important to calibrate the atmospheric neutrino calculations.

1 Introduction

For a more detailed study of neutrino oscillation phenomena observed by Super-Kamiokande, it is essential to minimize the systematic errors in the predicted energy spectra of neutrinos. In order to improve the accuracy of the predictions, a detailed understanding of (i) primary cosmic-ray intensities, (ii) hadronic interactions, and (iii) geomagnetic effect are indispensable.

As for absolute fluxes of cosmic-ray protons and helium nuclei below 100 GeV, which are relevant to atmospheric neutrinos observed as "fully contained events" in Super-Kamiokande, we have carried out very precise measurement by using the BESS detector (Sanuki et al. , 2000). Two completely independent experiments, the AMS (Alcaraz et al. , 2000a,b) and the BESS, show extremely good agreement in results of proton measurements with each other. There still remains some disagreement in helium flux. However, it leads to only small systematic errors in the atmospheric neutrino calculations.

Since production and decay process of muons are accompanied by neutrino productions, the intensities of muons correlate directly to the hadronic interactions. The geomagnetic effect is observed in the charge ratio of muons.

There have been many measurements of atmospheric muons (Hayman and A. W. Wolfendale , 1962; Bateman et al. , 1071; Allkofer et al. , 1971; Nandi and Sinha , 1972; Green et al. , 1979; Barbouti and Rastin , 1983; Rastine , 1984; Tsuji et al. , 1998; De Pascal et al. , 1993; Kremer et al. , 1999). Most of them utilized solid iron magnet spectrometers, in which multiple scattering made it difficult to measure the absolute rigidity reliably. An integrated flux above some energy was measured with a simple range detector in some of the previous observations. In these cases, it is not trivial to measure an absolute rigidity of incoming particle event by event. Most of the previous experiments did not obtain an absolute flux but normalized their observed spectrum to the "standard" value. In these kinds of measurements, small error in the momentum measurement leads to a large systematic error in the absolute flux, because atmospheric muons have very steep spectral shapes.

As will be described in section 2, the BESS spectrometer utilizes a thin superconducting solenoidal magnet. Its simple cylindrical geometry makes an estimation of the geometrical acceptance (SΩ) reliable. Furthermore, the live time was measured exactly. An absolute flux is therefore calculated irrespective of normalization. The overall efficiencies in the off-line analyses was kept high and corrections were kept small. Small corrections lead to small systematic errors. Thus the BESS spectrometer is an ideal instrument to measure the absolute spectra of cosmic-ray particles.

We measured absolute fluxes of atmospheric muons at different sites and at various altitudes with the BESS spectrometer. These measurements provide useful information about hadronic interactions and geomagnetic effect.

Correspondence to: sanuki@phys.s.u-tokyo.ac.jp

[†] Currently at Tohoku University, Sendai, Miyagi 980-8578, Japan

[‡] Currently at University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan

[*] deceased

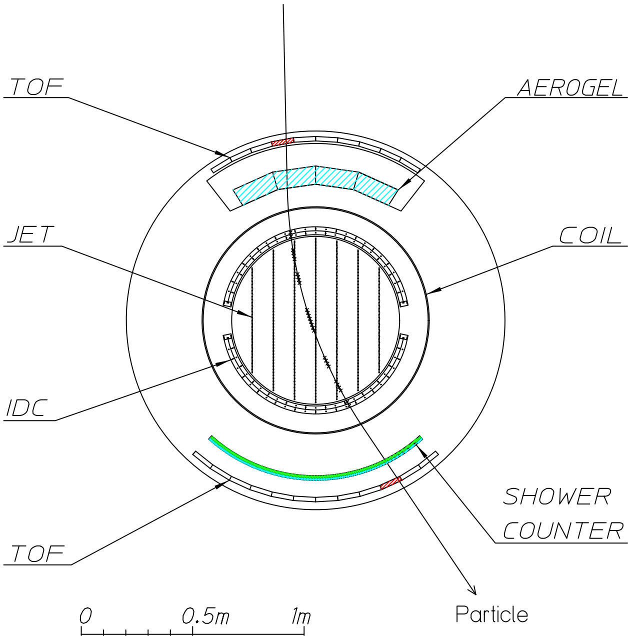

Fig. 1. Cross-sectional view of the BESS.

2 BESS spectrometer

The BESS (B̲aloon-borne E̲xperiment with a S̲uperconducting S̲pectrometer) detector is a high-resolution spectrometer with a large acceptance to perform highly sensitive searches for rare cosmic-ray components, as well as precise measurement of the absolute fluxes of various cosmic rays (Orito , 1987; Yamamoto et al. , 1994; Asaoka et al., 1998; Ajima et al. , 2000; Shikaze et al., 2000).

As shown in Figure 1, all detector components are arranged in a simple cylindrical configuration with a thin superconducting solenoidal magnet.

In the central region, the solenoid provides a uniform magnetic field of 1 Tesla. A magnetic-rigidity ($R \equiv pc/Ze$) of an incoming charged particle is measured by a tracking system, which consists of a JET-type drift chamber and two inner-drift-chambers (IDC's) inside the magnetic field. The deflection (R^{-1}) and its error (ΔR^{-1}) are calculated for each event by applying a circular fitting using up-to 28 hit points each with a spatial resolution of 200 μm.

Time-of-flight (TOF) hodoscopes provide the velocity (β) and energy loss (dE/dx) measurements. The time resolution for energetic protons in each counter was 55 ps rms, resulting in a β^{-1} resolution of 1.4 %.

An electromagnetic shower counter has been equipped for e/μ separation. It consists of a 2 X_0 thick lead plate and an acrylic $\check{\mathrm{C}}\mathrm{erenkov}$ counter.

Particle identification was performed by requiring proper dE/dx and 1/β as functions of rigidity. For muon identification, a signal from the electromagnetic shower counter was examined.

The simple cylindrical shape and the uniform magnetic field make it simple and reliable to determine the geometrical acceptance precisely.

Table 1. Experimental Conditions.

site	date		Atm. Pres. (g/cm^2)	R_c (GV)
Mt. Norikura	1999	September	743	11.5
Tsukuba	1995	December	1030	11.4
Lynn Lake ^{a} (1)	1997	July	1000	0.4
(2)	1998	August	1010	0.4
(3)	1999	July	984	0.4
Balloon Flight	1999	August	800–5	0.4

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[a] Three data sets, Lynn Lake (1 – 3), are compiled.

The live data-taking time was measured exactly by counting 1 MHz clock pulses with a scaler system gated by a "ready" status that controls the first-level trigger. The resultant live-time ratio was as high as 86.4 % and 98.8 % during the balloon and ground experiment, respectively.

Detailed analysis procedures and the discussion of errors are described in the previous papers (Sanuki et al. , 2000; Motoki , 2000).

3 Results

The experimental conditions of our measurements are summarized in Table 1.

3.1 Atmospheric muons at the top of mountain

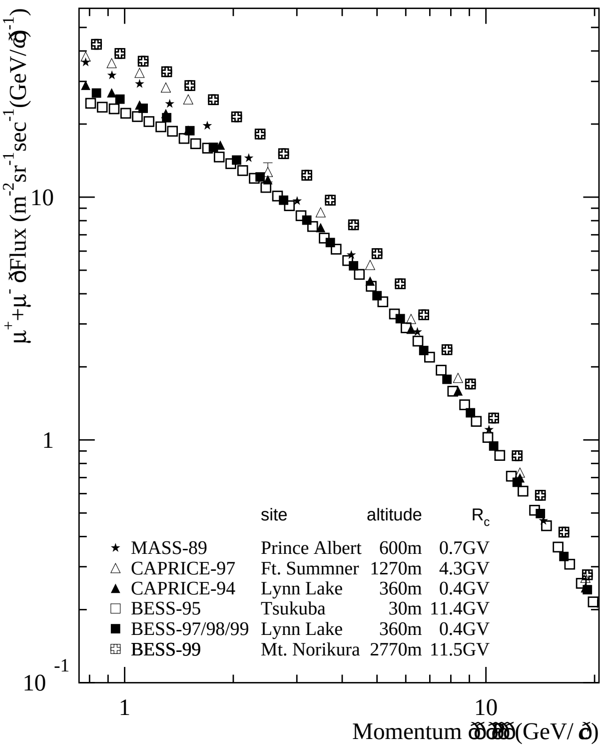

Fig. 2. Absolute differential muon spectrum.

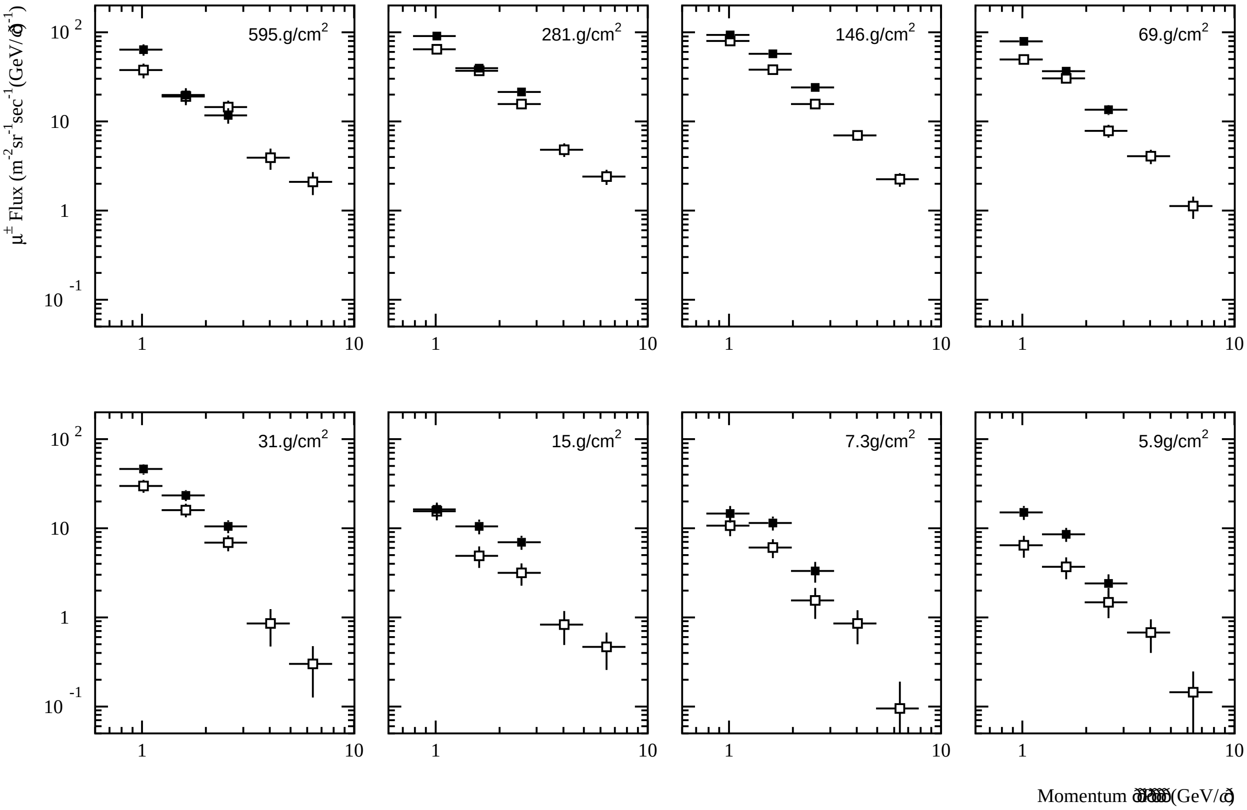

Fig. 3. Atmospheric μ^+ (closed squares) and μ^- (open squares) observed during the ascending period of the BESS-1999 balloon experiment. Mean value of the residual air is indicated in each graph.

Figure 2 shows the absolute differential spectrum of muons ($\mu^+ + \mu^-$) at the top of Mt. Norikura, Japan, together with other measurements (De Pascal et al. , 1993; Kremer et al. , 1999; Motoki , 2000). The muon intensity varies depending on environmental conditions. The altitude and cutoff rigidity for primary cosmic rays (R_c) are indicated in the figures.

As is seen in Figure 2, the higher muon flux is observed at higher altitude. This tendency comes from decays of muons. In a lower momentum region, muon flux is affected by geomagnetic effect.

3.2 Atmospheric muons in the atmosphere

We also measured the muon fluxes during the ascending and floating periods of the balloon experiments as shown in Figures 3 and 4.

A variation of the muon intensity along the air depth is affected by both muon production/decay and a structure of the atmosphere.

Compared to the atmospheric muon spectra at sea level, the spectra at a floating altitude are not so affected by a structure of the atmosphere, since there is only 5 g/cm^2 of residual air above the BESS detector. Thus these spectra shown in Figures 4 can provide a good anchor to estimate multiplicity and energy distribution of secondary particles in the hadronic interactions.

4 Discussions

The absolute fluxes and spectral shapes of atmospheric muons are directly related to the yield of neutrinos.

We have measured the atmospheric muon spectra at different sites and at various altitudes. The muon spectra in a low momentum region are sensitive to the effect of the geomagnetic field. Detailed study of the atmospheric muons will improve the accuracy in the estimation of the neutrino yield and the effect of the geomagnetic field.

Combining our results of atmospheric muon measurements, production and decay features of muons in the atmosphere can be reproduced. There exists n relation between muon decay and a structure of the atmosphere, because energy loss rate is affected by a column density of air. For a more precise study of muon decay, i.e. neutrino production, it is very important to investigate the structure of the atmosphere up to the top of the atmosphere. Precise measurements of atmospheric muons, as well as primary cosmic rays, are indispensable for accurate atmospheric neutrino calculations.

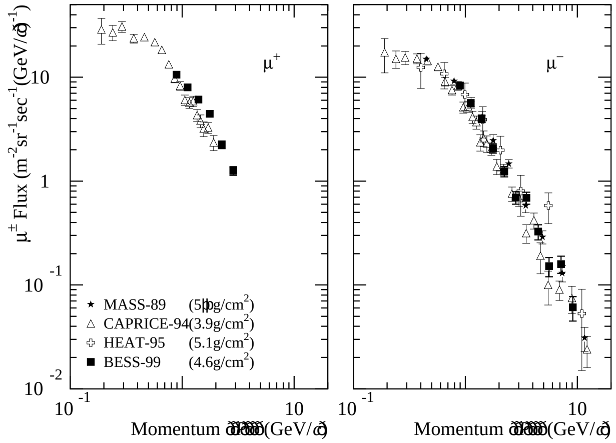

Fig. 4. Atmospheric μ^+ (left) and μ^- (right) at a floating altitude measured during the BESS-1999 balloon experiment. Other measurements from previous experiments (Brunetti et al. , 1996; Boezio et al. , 1999; Coutu et al. , 1998) are also indicated. Residual air in each experiment is slightly different.

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