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Atmospheric muon measurements I: Vertical measurements

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Abstract. The atmospheric muon measurements at sea level were better than the ones we have presented before. We report more stable results of the absolute differential muon fluxes in vertical, in the momentum range between 1.5 to 100 GeV/c. These results are compared with theoretical calculations and experimental muon measurements.

1 Introduction

A lot of muon measurements have been reported in vertical observations (Alkofer et al., 1971; Ayre et al., 1975; Rastin, 1984; Nandi et al., 1972; Bateman et al., 1971; Hayman and Wolfendale, 1962; Green et al., 1979; Tsuji et al., 1998; De Pascale et al., 1993; Kremer et al., 1999; Motoki et al., 2000). The precise measurements are significant for the decisions of the primary flux and the models of atmospheric showers. And this results also can be used to check atmospheric neutrino calculations (Honda et al., 1995; Volkova, 1980; Mitsui et al., 1986; Butkevich et al., 1989; Lipari, 2000; Gaisser et al., 1988; Bar et al., 1989; Bugaev and Naumov, 1989; Lee and Koh, 1990). These calculations are very significant as the interpretation of the neutrino oscillation from the deep under ground experiments (Fukuda et al., 1998; Becker-Szendy et al., 1992). Muon fluxes are measured using two type of magnet spectrometers. One is measured by solid iron magnet and the other is by super conducting magnet. Muon have been measured using solid iron magnet since about 50 yeas before. Recently, the detectors have measured using super conducting magnet (De Pascale et al., 1993; Kremer et al., 1999; Motoki et al., 2000). The results of muon flux measurements between two types are reported to have same difference (Hebbeker and Timmermans, 2001). The difference is about 13.4% against the absolute value using solid iron magnet. Solid iron detector cannot avoid large coulomb scattering effect. Low momentum events scatter in the high momentum events. The reason of the difference results between two type detectors are cause by coulomb scatter in solid iron magnet. In this paper, we show several analyzed results of muon fluxes and indicate the reason of the difference is the effect of the coulomb scattering in solid iron magnet.

2 OKAYAMA telescope

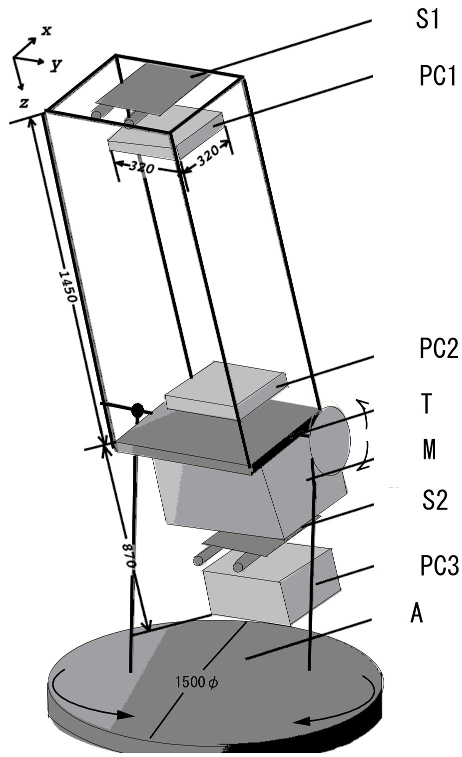

Fig. 1. A sketch of OKAYAMA cosmic-ray telescope. S1 and S2: scintillation counters, PC1, PC2 and PC3: position chambers, M: iron core magnet, A: altazimuthal turn table, T: telescope mounting.

The OKAYAMA cosmic-ray telescope was transferred from

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bottom to top floor of Okayama University in 2000. The detector is equipped 28 m above sea level. The wall thickness is thin and uniform compared with previous our experiment. Fig. 1 shows a sketch of the telescope. The telescope consists of trigger counters(scintillators)(S1 and S2), position chambers(multi-wire proportional chambers used as drift chambers)(PC1, PC2 and PC3), an iron core magnet(M), a telescope mounting(T) and altazimuthal turntable(A). More detail constructions are described in the reference (Yamashita et al., 1995; Tsuji et al., 1998). We identified an observed particle as a muon if it passed through the telescope in a straight line without substantial interactions and if it penetrated at least 300 g/cm^2 of material including the telescope mounting and the solid iron magnet loaded in the telescope. The OKAYAMA cosmic-ray telescope has some original characteristics which are moving by a servomotor mechanism thus allowing any azimuthal and zenith angle to be used , and measuring the incoming directions, the momentum and the charge sign of incident cosmic-ray muon. The telescope equipped these characteristics is suitable for the measurements of muons not only in vertical but also in any directions.

3 Results

Hebbeker and Timmermans (2001) show the results of muon fluxes compiled almost all over the measurements. They show the following calculations.

$$\begin{aligned} H(y) &= H_1 \cdot (y^3/2 - 5y^2/2 + 3y) \\ &\quad + H_2 \cdot (-2y^3/3 + 3y^2 - 10y/3 + 1) \\ &\quad + H_3 \cdot (y^3/6 - y^2/2 + y/3) \\ &\quad + S_2 \cdot (y^3/3 - 2y^2 + 11y/3 - 2) \\ y &= C \cdot \log_{10}(p/\mathrm{GeV}) \\ F(p) &= 10^{H(y)} \mathrm{m}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}\mathrm{GeV}^{-1} \end{aligned} \tag{1}$$

Here, $H_1 = 0.135 \pm 0.002$, $H_2 = -2.529 \pm 0.004$, $H_3 = -5.76 \pm 0.03$and $S_2 = -2.10 \pm 0.03$. Constant value C is 0.937 ± 0.012 in case of solid iron magnet, 0.811 ± 0.007 in case of super-conducting magnet. The absolute flux difference shows 0.126 which correspond 13.4% against the solid iron magnet value. We analyzed our data to indicate that the reason of the difference is caused by coulomb scattering in the solid iron magnet. Analyzed data was used from 27 August to 26 October in 2000. Total observation time is 379h.

3.1 Analyses 1

Muon momentum is calculated by the deflective angle in the magnetic field. The deflective angle ψ determines the momentum P_0 after passing through the material, as follows:

$$P_0 = 300 \times B \times L/\sin(\psi) \ \ (\mathrm{eV/c}), \tag{2}$$

here L is the depth of the magnet and B is the magnetic field. P_0 is converted to sea level muon momentum P after computing the energy-loss values of the muon passing through the materials. The trajectory passing through the telescope cross outside the magnet in case muon affected large coulomb scattering. We select muon events near the center of magnet to avoid muon events suffering large coulomb scattering. Fig. 2 shows muon fluxes (white square plots) which cross point of the trajectory in Z axis of Fig. 1 is within 72 cm from the center of magnet. The error bars show statistical errors only.

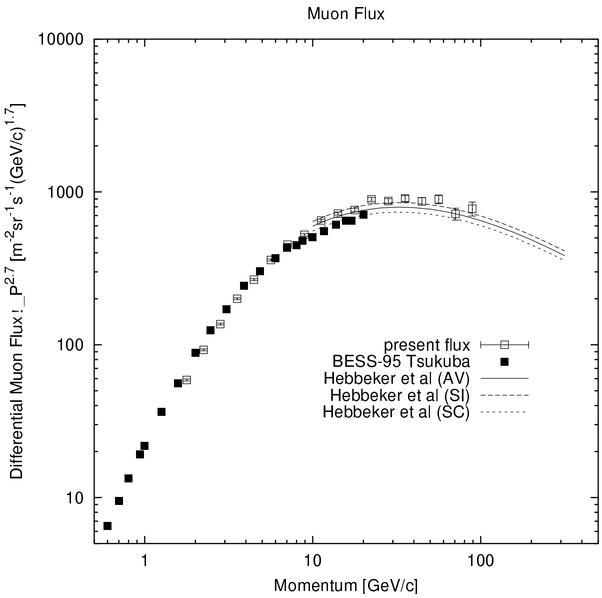

Fig. 2. Muon fluxes. White squares: Present fluxes were adopted within 72 cm from the center of the magnet for the Z axis in Fig. 1. Black squares: BESS-95 results. Dashed line: Calculated muon fluxes using solid iron magnet. Dotted line: Calculated muon fluxes using super-conducting magnet. Solid line: Averaged Muon fluxes using solid iron magnet and super-conducting magnet.

The black square plots show the result BESS-95 using super-conducting magnet in Tsukuba (Motoki et al., 2000) below 20 GeV/c and the lines are calculations by Hebbeker and Timmermans (2001) above 10 GeV/c. Dashed line shows calculated muon fluxes compiling the experimental data using solid iron magnet and dotted line shows using super-conducting magnet. Solid line shows averaged the values of using two type of magnet. Our analyzed data adopted only crossing muon trajectories near the center of magnet almost fitted the calculated value using solid iron magnet above 10 GeV/c.

3.2 Simulations

We tried using simulated data to reproduction our measurements results. If real muon fluxes are those of compiling the experimental data using super-conducting magnet, our results should be explained containing large coulomb scattering events. We calculated our results using our detector factor (magnetic field, chamber resolutions and so on,) and simulated muon fluxes using super-conducting magnet. The probability weights of muon fluxes were used the results of BESS-95 below 10 GeV/c and the calculations using super-conducting magnet above 10 GeV/c. Energy loss and multiple scattering were followed Review of Perticle Physics (2000). Our calculated data is selected in the same condition shown in Fig. 2 to compared with measured events in Fig. 2 and not selected to compared with no modified experimental events which contain suffering large coulomb scattering. Fig. 3 shows the calculated results. White square plots

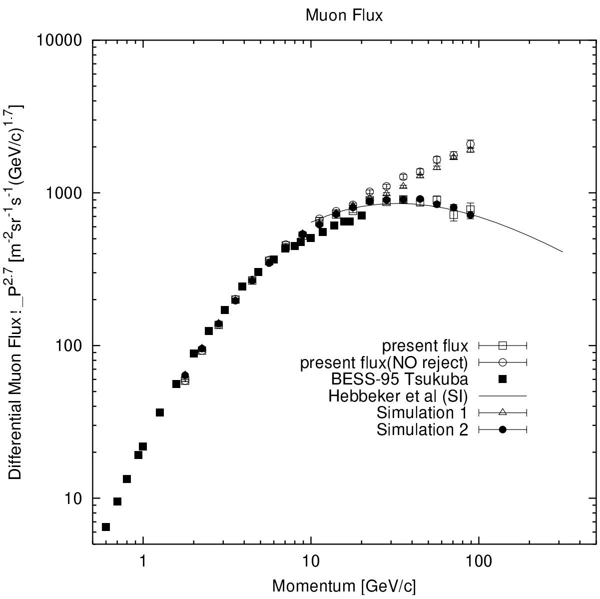

Fig. 3. Muon fluxes. White squares: Present fluxes adopted within 72 cm from the center of the magnet. White circles: Present fluxes without a certain selection to cut large coulomb scattering. Black squares: BESS-95 results. Solid line: Calculated muon fluxes using solid iron magnet. White triangles: Calculated value under the same analyzed conditions of white squares. Black circles: Calculated value under the same analyzed conditions of white circles.

"present flux" and black square plots "BESS-95 Tsukuba"are same meaning in Fig. 2 and solid line shows muon fluxes compiling the experimental data using solid iron magnet.
White circle plots, "present flux(NO reject)" show no modified experimental events without a certain selection to cut large coulomb scattering events. White triangle plots "Simulation 1" are calculated under the same analyzed conditions of "present flux(NO reject)". Also black circle plots "Simulation 2" are calculated under the conditions of "present flux". The error bars show statistical errors only. Two simulations are shown in good agreement with our measurement results. "Simulation 2" are almost fitted Solid line. It means that the constant C of the equation (1) seems 0.811 ± 0.007 more reliable than another value and the difference of two constant value originate the coulomb scattering effect in the solid iron magnet.

3.3 Analyses 2

We analyzed muon data strictly to avoid large coulomb scattering. Muon data are selected that the cross point of the trajectory is within 72 cm from the center of magnet described in subsection 3.1. And muon data with deflective angles in magnetic field (in the X-Z plane in Fig.1 in the reference (Tsuji et al., 2001)) less than the scattered angle (in Y-Z plane) are also rejected. Fig. 4 shows the results. The lines and black square plots represent same results in Fig. 2. White square plot show the result in above selections. Compared with the result in Fig. 4, this analyzed result in this analyses a little close to the calculation muon fluxes in case of using super conducting magnet. However this analyzed results do not almost fit with calculated line using super conducting magnet detector. We need new analyses to improve avoiding coulomb scattering effect from muon fluxes using iron solid magnet.

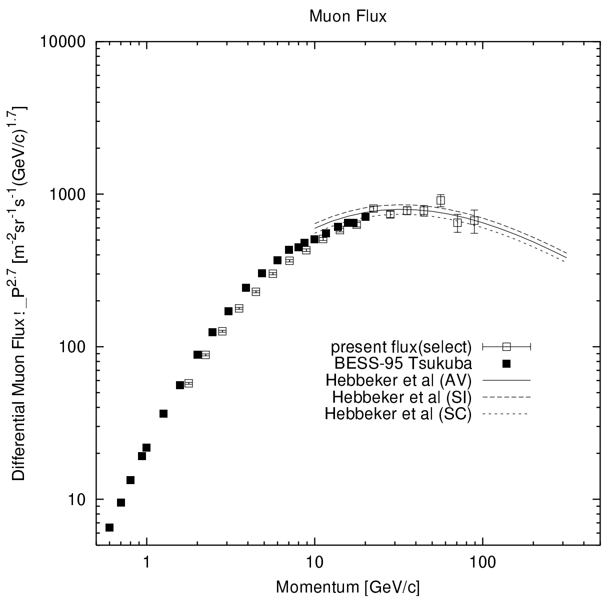

Fig. 4. Muon fluxes. White squares: Present fluxes were adopted within 72 cm from the center of the magnet for the Z axis and the deflective angles in magnetic field (in X-Z plane) less than the scattered angle (in Y-Z plane) in Fig. 1 and . Black squares: BESS-95 results. Dashed line: Calculated muon fluxes using solid iron magnet. Dotted line: Calculated muon fluxes using super-conducting magnet. Solid line: Averaged Muon fluxes using solid iron magnet and super-conducting magnet

4 Conclusion

This paper resolves the reason of the difference of the absolute flux between the detectors with solid iron magnet and with super conducting magnet. Muon fluxes in the detector using solid iron magnet tendency to show the large value by large coulomb scattering in the solid iron magnet. The constant in the calculation (1) is 0.811 ± 0.007 more reliable.

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