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# Atmospheric muon measurements II: Zenith angular dependence

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**Abstract.** The altazimuthal counter telescope with a magnet spectrometer, the OKAYAMA telescope is able to move by servo-motor mechanism for any azimuth and zenith angles. The muons at sea level have been observed in vertical and in zenith angle 40°. We are able to get muon data more stable and lower momentum than previous presented ones. The new muon data are analyzed in the momentum range 1.5 to 100 GeV/c. We report more precise results of the muon measurements, especially the muon charge ratio about the zenith angle dependence and discuss with previous other experimental results near vertical or large zenith angular region.

## 1 Introduction

Much atmospheric muon measurements have done at sea level. Almost of the experiments has done in the vertical (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). And several group measured muons in large zenith angles (Matsuno et al., 1984; Allkofer et al., 1981,1985; Jokisch et al., 1979; Kellogg et al., 1978). One of the significant of measuring atmospheric muons investigates the influence of kaons for atmospheric muon productions. Above a few hundred GeV, the influence of kaons for the muon charge ratio is predicted to be growing (Gaisser, 1990). MUTRON showed the results of slightly growing muon charge ratio above 0.1 TeV/c at 89° (Matsuno et al., 1984). It is reported that several muon charge ratios in vertical are tendency to have the 'peak' at about 30GeV (Hebbeker and Timmermans, 2001). Though this peak is within the error, this tendency to have the peak at about 30GeV may have a phenomenon originated primary cosmic ray like a contribution of kaon. Several zenith angle dependences of the muon measurements are needed to resolve above the phenomenon. OKAYAMA cosmic-ray telescope have some suitable functions to measure atmospheric muons in any directions. The functions are following. Moving by servomechanism for any azimuthal and zenith angles. Measuring the incoming direction, the momentum and the charge sign of an incident cosmic-ray muon. We report atmospheric charge ratios in vertical and in 40°± 5°zenith angles. The measurements in 40°± 5°zenith angles is that in median angles between 0°and 90°. The measurements around this zenith angle region are not almost reported. Momentum range is from 1.5 to 100 GeV/c, we remarked the results about 30GeV/c. In this analyses, the peaks at about 30 GeV/c were not seen in the results in vertical and in 40 °zenith angles. The results are compared with previous other and our published experimental results.

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## 2 Muon data selection and observation period

### 2.1 Muon data selection

Fig. 1 shows a scale diagram of the OKAYAMA cosmic-ray telescope. Detail telescope structures are published in the references (Yamashita et al., 1995; Tsuji et al., 1998). The telescope is located 34°40' N latitude, 133°56' E longitude and 28 m above sea level. The cut-off rigidity is 12 GV. Measured muons are selected to avoid large coulomb scattering events. Main selections to avoid large coulomb scatter are following, the cross point of the trajectory on the X-Z plane in Fig. 1 is within 72 cm from the center of the magnet and the scattered angle on the Y-Z plane is less than a deflective angle $\psi$ on the X-Z plane.

### 2.2 observation period

Analyzed muon data in vertical is used from 27 August to 26 October 2000 and also added from 27 September 1992 to 8 September 1996 to reduce statistical errors. Total observation time is 5404h. The muon data in zenith angle 40°± 5°is used from 4 September to 19 October 2000. Total observation time is 765h.

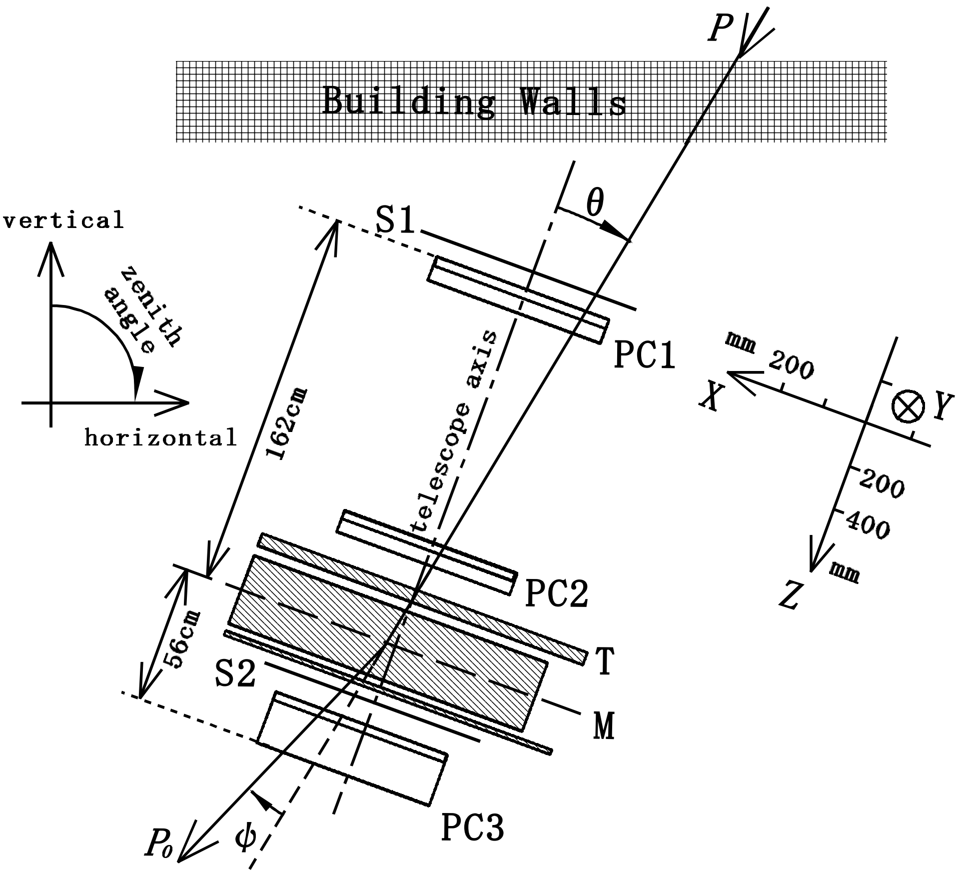


**Fig. 1.** A cross-sectional view of the altazimuthal particle telescope with the magnet spectrometer, the OKAYAMA cosmic-ray telescope and trajectory of a charged particle through the solid iron magnet. S1 and S2, scintillation counters; PC1, PC2 and PC3, position chambers; M, iron core magnet; T, telescope mounting. $\theta$, incident angle; $\psi$, deflection angle; $P_0$, $P_1$ and $P_2$, momentum at out-side of walls, the top of the telescope and beneath of the magnet in the telescope.

## 3 Results

### 3.1 Muon charge ratio in vertical

The muon charge ratio is shown in Fig. 2 as black circle plots. We collect data set with momentum width $\Delta P = 10^{0.2}$ GeV/c. The error bars show one standard deviation $\sigma$ determined following equation,

$$\sigma = \frac{f^+}{f^-}\left(\frac{1}{N^+} + \frac{1}{N^-}\right)^{1/2} \tag{1}$$

where $f^+, f^-, N^+$ and $N^-$ show the flux and number of positive and negative muons respectively. White square plots show CAPRICE 94 results Kremer et al. (1999) and white triangle plots show Rastin results (Rastin, 1984). CAPRICE experiment reported muon measurements in 2 locations.

CAPRICE 94 experiment did at an atmospheric depth of 1000 g/cm$^2$ and CAPRICE 97 did at an atmospheric depth of 886 g/cm$^2$. We select the results of CAPRICE 94 to compare with our results since atmospheric depth is almost same our place. The results with the momentum range between 8 GeV/c and 20 GeV/c agree with the other experiments. The results less than 8 GeV/c shows not good agreement other experiments. Muons with this momentum region are considered to be effected geomagnetic field. This difference caused by observation places. The results more than 20 GeV/c show the good agreement with Rastin's ones except for one with the momentum 50.1 GeV/c. Our results and Rastin's ones are shown no peak around 30 GeV/c, only CAPRICE 94 results presents the peak. The lines show the calculated results published by Hebbeker and Timmermans (2001). Their equation is following,

$$R_\mu = 1.268 \pm \left[0.008 + 0.0002 \cdot \frac{p}{\mathrm{GeV}}\right], \tag{2}$$

in the momentum range 10 to 300 GeV. Solid line shows the mean value in the equation (2). Dashed lines show upper and lower limit in the equation (2). Our charge ratios more than 7.9GeV/c are shown within the error band except for one with the momentum 50.1 GeV/c. As the paper (Tsuji et al., 2001) shows the coulomb scattering effects in the solid iron magnet, our analyzed data are insufficient since analyzed events have some probability to contained large coulomb scattering events. Our results more than 10 GeV/c seem closer Rastin's ones than CAPRICE 94. Rastin

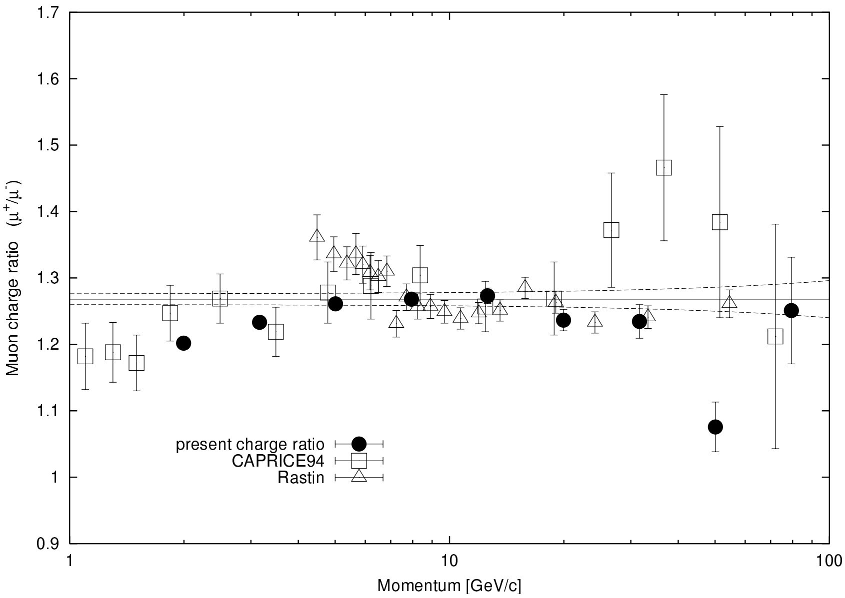


**Fig. 2.** Muon charge ratios. Black circles: Present muon charge ratios. White squares: CAPRICE 94 results (Kremer et al., 1999) White triangles: Rastin results (Rastin, 1984) Solid line: Calculated value of mean charge ratio by Hebbeker and Timmermans (2001). Dashed lines: Calculated value of upper and lower charge ratio by Hebbeker and Timmermans (2001). The lines are following equation (2)

also use solid iron magnet to measure atmospheric muons. Muon charge ratio may also have the difference between using solid iron magnet and super conducting magnet related coulomb scattering effects. In this point, we need to proved the way of past analyses.

### 3.2 Muon charge ratio in zenith angle 40°± 5°

We measured muons 8 azimuthal directions in the zenith angle 40°± 5°. The muon events at a certain direction are fluctuated for the geomagnetic field effects especially in the low momentum region. We combine all muon data together and analyzed to decrease the geomagnetic field effects. Fig. 3 shows the results. The data set combined each momentum width $\Delta P = 10^{0.2}$ GeV/c. Black circle plots shows the results in this time and white square plots shows previous our results(Tsuji et al. (1998), here after Paper I.). Error bars shows one standard deviation and following equation (1). White square plots show the charge ratio in the zenith angle 38 °± 4°and north-east and north-west directions. The line shows the measured value by Burnett (Burnett et al., 1973). This line shows the averaged charge ratio above 50 GeV/c. The value $R$ in zenith angle 38°± 4°is,

$$R = 1.241 \pm 0.035. \qquad (3)$$

The results in this time are agree with previous our results. More than 20 GeV/c, muon charge ratio shows to fit a line roughly. Remarkable peak measured by CAPRICE 94 at around 30 GeV/c in vertical dose not seen in the momentum range 1.5 to 100 GeV/c in zenith angle 40°± 5°. Comparison with our results in vertical, muon charge ratio tends to have a small peak around 10 GeV/c.

## 4 Conclusion

We presented atmospheric muon charge ratios in vertical and in zenith angle 40°. Our results of charge ratio in vertical more than 10 GeV/c tend to closer Rastin's ones than CAPRICE 94. We do not have a remarkable peak around about 30 GeV/c in the measurements in vertical and zenith angle 40°.

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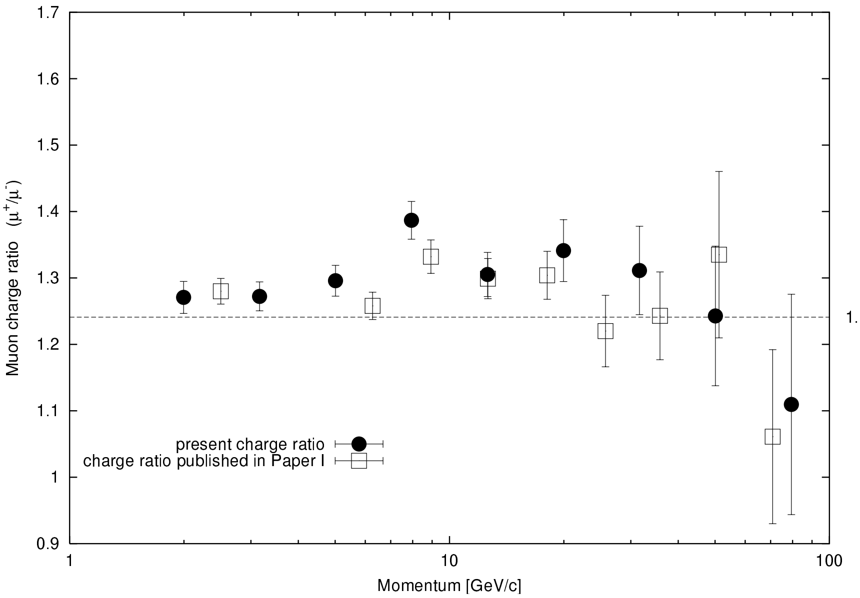


**Fig. 3.** Muon charge ratios. Black circles: Present muon charge ratios. White squares: Previous reported result published in Paper I (Tsuji et al., 1998) Dashed line: averaged charge ratio above 50 GeV/c measured by Burnett et al. (1973)

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