# Measurement of Cosmic-Ray Muon Spectrum and Charge Ratio at Large Zenith Angles in the Momentum Range 100 GeV/c to 10 TeV/c Using a Magnet Spectrograph

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The cosmic-ray muon momentum spectrum and charge ratio up to momenta $\simeq$ 10 TeV/$c$ have been measured with high accuracy. The power index of the differential spectrum of parent mesons at production gradually increases with momentum and becomes 2.87 $\pm$0.06 in the momentum range 1 to 10 TeV/$c$. The charge ratio is almost constant at a value of 1.25$\pm$0.05 from 0.1 to 10 TeV/$c$.

The cosmic-ray muon spectrum at energies greater than 1 TeV has been so far obtained only by "indirect" methods based on the range-energy relation[1-3] or burst measurements.[4-7] "Direct" measurement with use of a magnet spectrograph in the past has been restricted to the energy range less than $E_\mu \lesssim 1$ TeV. The advantage of the magnet spectrograph method over the others lies in the accuracy of momentum determination.

We have constructed a large solid iron magnet spectrograph named MUTRON, which has a large enough geometrical factor to allow measurement of muon fluxes between $E_\mu$ = 100 GeV–10 TeV, in spite of the very low value of the flux. This is the first report of the muon momentum spectrum and charge ratio beyond a few TeV measured by use of this spectrograph.

A schematic view of MUTRON is given in Fig. 1. The spectrograph consists of two solid iron magnets with a total thickness of 8 m, four trays of multiwire proportional counters (MWPC) for triggering, and eight trays of wire spark cham-

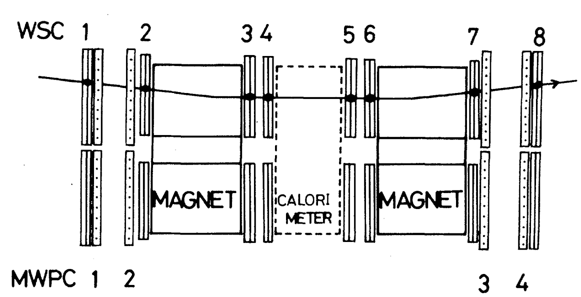


FIG. 1. Schematic view (vertical cross section) of muon spectrometer MUTRON.

bers (WSC) for the track determination. The $\int B\,dl$ value of each of the magnets is 64 m kG. The calorimeter located between the two magnets is used to study interaction of muons of known energy. Results from the study will be reported elsewhere. The MWPC trigger logic is set to trigger the spark chambers only for muons with energy $\gtrsim 100$ GeV.[8]

Muons in the zenith-angle range 87°–90° are accepted by the spectrograph. The weighted mean zenith angle is found to be 88.8°. The geometrical acceptance of the spectrometer is 1360 $\text{cm}^2$ sr, almost independent of energy for muons with energy greater than 300 GeV. The detection efficiency of the MWPC system is determined to be $(95.0 \pm 0.2)\%$ and the triggering rate is $(1.00 \pm 0.02)$/min. The efficiency of one spark-chamber gap is approximately 90% for a single track, when helium gas is used.

The resolution of the wire spark chambers, obtained by the use of actual muon tracks, is ~1.3 mm for muons with $E_\mu \geq 800$ GeV. The maximum detectable momentum (MDM) of the spectrometer is a function of the number of sparks along the muon trajectory; in the case where all 16 spark-chamber gaps fired the MDM is ~13.5 TeV/$c$. Detailed descriptions of the multiwire proportional counters and the spark chambers have been reported earlier.[8,9]

The muon momentum is determined from the deflection of its trajectory in the known magnetic field. The trajectory is determined by the eight layers of spark chambers. A total of $1.868 \times 10^5$ events ($P_\mu \gtrsim 100$ GeV/$c$) obtained over a period of 3110 hours has been analyzed. Each muon trajectory is fit by least-squares method to the hypothesis that a noninteracting singly charged particle passes through the known magnetic field within the specified geometry. The events with reduced $\chi^2$ less than 7.3 are regarded as muons. If any spark chamber shows more than one spark, the spark giving the least $\chi^2$ in the fit is choosen as the coordinate of the muon. We demand that at least four chambers must fire for the event to be accepted. In this limiting case, the MDM is degraded to about 2 TeV/$c$.

As stated earlier, precision in muon momentum determination improves with the number of spark chambers fired. We, therefore, made a further cut in muon candidates events according to MDM, giving a muon spectrum based on events for which accuracy of track determination corresponds to MDM higher than 10 TeV/$c$. (The rate of events for which the recorded data give MDM higher than 10 TeV/$c$ is 63.3% of all muon candidate events.) It should be noted that the cuts are not momentum dependent and therefore do not affect our results on the shape of the spectrum.

Since the muon momentum spectrum is very steep, it is possible that there is significant distortion of the shape of the spectrum due to the finite spatial resolution of the spark chambers and to multiple scattering of muons in the iron. These effects can cause a given momentum interval to contain events whose true momenta lie outside the interval, with values that are either higher or lower.

The corrected differential momentum spectrum of muons at sea level thus obtained is further corrected for the effects of muon decay and the energy loss $\Delta E_\mu$ of muons[10] in the atmosphere and iron magnet to obtain the differential spectrum of muons at production.

In order to compare our results with those obtained by others, we determine the relationship between the sea-level muon spectrum and the production spectrum of the parent particles of muons, namely pions and kaons, following the standard method used and described[11] in the past. We fit the differential energy spectrum of muons to the expression

$$N(E_\mu,\theta)dE_\mu = AE_\mu^{-\gamma}[r_\pi^{\gamma-1}B_\pi/(E_\mu+B_\pi) + (K/\pi)r_K^{\gamma-1}(\text{branching ratio})B_K/(E_\mu+B_K)], \quad (1)$$

to obtain the value of $\gamma$, the power index of the differential spectrum of parent mesons at production. Here $E_\mu$ represents the muon energy at production, which is obtained by adding the energy loss in the air and solid iron magnets,

$$\Delta E_\mu = (2.5 + 3.25\times 10^{-3}E_\mu)10^{-3}X(\theta^*) + 3.15(2.0 + 8.0\times 10^{-3}E_\mu),$$

to the energy observed as the muon exits from the spectrograph. The constants $B_\pi$ and $B_K$ are given by $B_\pi = B_\pi(0)\sec\theta^*$ and $B_K = B_K(0)\sec\theta^*$, where $\theta^*$ represents the zenith angle at muon production. For example, for $\theta = 89°$ ($\theta^* = 84°$), $B_\pi = 880$ GeV, $B_K = 4200$ GeV, $X(89°) = 27\,600$ g $\text{cm}^{-2}$, $r_\pi = 0.76$, $r_K = 0.52$, and effective $K/\pi$ ratio[12] $(K/\pi) = 2.4 \times 0.15$ and branching ratio $= 0.63$. We find that the $\chi^2$ fits show a slight dependency of $\gamma$ on the assumed value of the $K/\pi$ ratio.

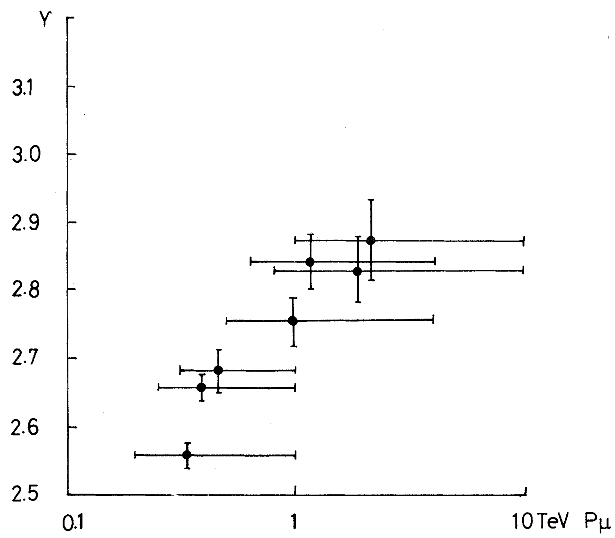


FIG. 2. The $\gamma$ value of parent mesons at the production. The $\chi^2$ fits are done over different muon momentum ranges shown by the horizontal bars attached to each datum point.

The values of $\gamma$ and $A$ obtained for minimum $\chi^2$ for the momentum range $P_\mu = 1-10$ TeV/$c$ are $\gamma = 2.87 \pm 0.06$ and $A = 0.373 \pm 0.030$ ($\chi^2 = 6.2$ for 9 degrees of freedom). The $\gamma$ value which we obtained is shown as a function of energy in Fig. 2. As can be seen from Fig. 2, the $\gamma$ value gradually increases with the mean muon momentum up to ~1 TeV/$c$. The absolute value of muon integral flux is $I(E_\mu > 1\ \text{TeV}) = (1.46 \pm 0.15) \times 10^{-7}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$ at a mean zenith angle of 88.8°. This integral flux is 17% less than the flux calculated by Murakami *et al.*[13] for $\gamma = 2.80$.

The results on muon charge ratio which we have obtained are shown in Fig. 3. This is the first determination of the cosmic-ray muon charge ratio over 1 TeV obtained by the *direct* method. The charge ratio is almost constant at a value of $1.25 \pm 0.05$ over the wide momentum range $P_\mu = 100$ GeV/$c$–10 TeV/$c$. Our result is in agreement with the results of previous direct experiments[14] below 1 TeV and also with the indirect measurements by Ahley, Keuffel, and Larsen[15] at $E_\mu > 1$ TeV. We have not observed the enhancement of charge ratio with increasing energies as reported by Allkofer *et al.*[14]

Our result on $\gamma$ for the momentum range 1–10 TeV/$c$ is in agreement within the stated errors with the previous results obtained by the muon emulsion chamber in the momentum range[4] 1–5 TeV/$c$ ($2.76 \pm 0.12$) and in the horizontal air-shower experiment[6] ($2.76 \pm 0.20$) in the momentum range 2–200 TeV/$c$. However, the errors in the present result are far smaller than in those results. Our result obtained by the direct method, however, gives a larger value of $\gamma$ than that obtained by the indirect method, applying the range-energy relation to depth-intensity measurements[1] ($2.66 \pm 0.05$) in the momentum range 200 GeV/$c$–

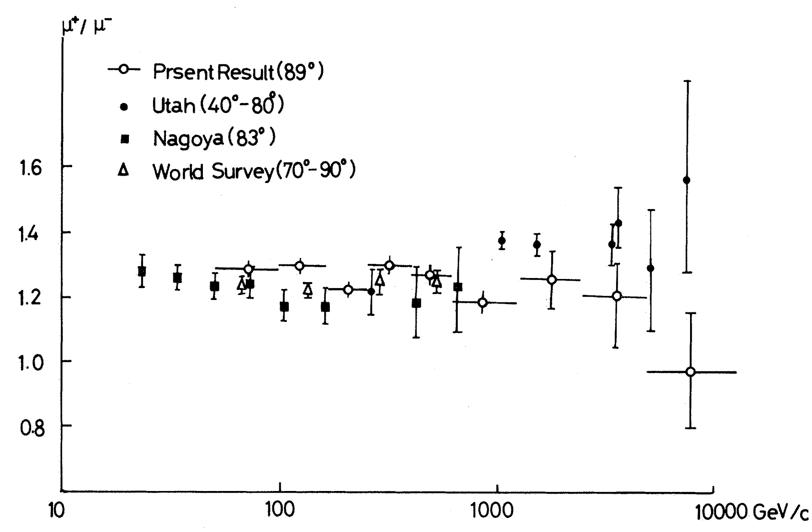


FIG. 3. Muon charge ratio measured by MUTRON (open circles). Previous resluts of Ahley, Keuffel, and Larson (closed circles; Ref. 15) and of Iida (closed squares; Ref. 14) are presented, together with world survey data of Allkofer, Carsten, Dau, and Jokisch (open triangles; Ref. 14).

40 TeV/$c$. Here we remark that the $\gamma$ value in the lower-momentum range $250 < P_\mu < 1000$ GeV/$c$ obtained from our experiment is $2.56 \pm 0.016$, which is consistent with the previous results by magnet spectrograph.[14]

It is interesting to note that the slope of the integral spectrum of parent mesons deduced from the present experiment and the integral spectrum obtained from emulsion chamber experiments at airplane altitude ($2.90 \pm 0.07$) in the momentum range[16] 1–40 TeV/$c$ and at mountain altitude[17] ($2.90 \pm 0.05$) coincide within the experimental errors in the momentum range 1.5–100 TeV/$c$, i.e., the hadron flux at three different altitudes [~ 100, 260, and 550 g] shows the same attenuation. This result indicates that the spectrum of the primary cosmic-ray flux, which contributes to muon production, gradually becomes steeper at ~ 10 TeV and the scaling of hadron production at $X_F > 0.15$ ($\simeq 2P^{\text{c.m.}}/\sqrt{s}$) holds in this energy range.

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[1]M. R. Krishawamy *et al.*, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977), Vol. 6, p. 85.

[2]W. R. Sheldon *et al.*, Phys. Rev. D 17, 114 (1978).

[3]M. F. Crouch *et al.*, Phys. Rev. D 18, 2239 (1978).

[4]M. Akashi *et al.*, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Insitut für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 6, p. 2037; K. Mizutani *et al.*, to be published.

[5]T. P. Amineva *et al.*, in *Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, Colorado, 1973* (University of Denver, Colo., 1973), Vol. 3, p. 1788.

[6]M. Nagano *et al.*, J. Phys. Soc. Jpn. 30, 33 (1971); S. Mikamo *et al.*, private communication.

[7]S. Chin *et al.*, Nuovo Cimento 413, 177 (1971).

[8]Trigger counters: see K. Honda *et al.*, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Insitut für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 9, p. 335; Y. Teramoto *et al.*, Nucl. Instrum. Methods 150, 387 (1978).

[9]Spark chambers: see Y. Ohashi *et al.*, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Insitut für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 9, p. 3301. Data handling: see Y. Muraki *et al.*, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Insitut für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 9, p. 3353.

[10]K. Kobayakawa, in *Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, Colorado, 1973* (University of Denver, Colo., 1973), Vol. 3, p. 1746.

[11]K. Maeda, J. Geophys. Res. 69, 1725 (1964); P. J. Hayman and A. W. Wolfendale, Proc. Phys. Soc. 80, 710 (1962); R. M. Bull, W. F. Nash, and B. C. Rastin, Nuovo Cimento 40A, 365 (1965); O. C. Allkofer, K. Carstensen, and W. D. Dau, Phys. Lett. 36B, 425 (1971).

[12]The factor 2.4 in the expression for effective $K/\pi$ ratio comes from the correct treatment of the kaon decay term of Eq. (1).

[13]K. Murakami *et al.*, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977), Vol. 6, p. 143.

[14]S. Iida, Nuovo Cimento 26B, 559 (1975); T. H. Burnett *et al.*, Phys. Rev. Lett., 30, 937 (1975); T. L. Asatiani *et al.*, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Insitut für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 6, p. 2024; M. G. Thompson *et al.*, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria 1977), Vol. 6, p. 21; R. G. Kellog, H. Kasha, and R. C. Larsen, Phys. Rev. 17, 98 (1978); O. C. Allkofer *et al.*, Phys. Rev. Lett. 41, 832 (1978).

[15]G. K. Ahley, II, J. W. Keuffel, and M. O. Larson, Phys. Rev. 12, 20 (1975).

[16]Y. Takahashi *et al.*, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977), Vol. 7, p. 408.

[17]M. Akashi *et al.*, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977), Vol. 7, p. 430.