PHYSICAL REVIEW D VOLUME 13, NUMBER 3 1 FEBRUARY 1976

Absolute low-latitude sea-level muon intensity at large zenith angle

Deba Prasad Bhattacharyya*

Indian Association for the Cultivation of Science, Jadavpur, Calcutta-700032, India

(Received 24 October 1973; revised manuscript received 28 July 1975)

The absolute sea-level cosmic-ray muon intensity has been estimated by using a flash-tube range spectrograph at axial zenith angles 75°–85° W near the geomagnetic equator in the cutoff-momentum region 0.4 GeV/c. The measured absolute muon intensity agrees with the results calculated in the manner of Ashton *et al.*, assuming $K/\pi = 0$ for zenith angles up to 81° W and $K/\pi = 0.4$ for 85° W. The angular distribution of muons obeys a cosine-square law. The measured absolute integral muon spectrum at axial zenith angle 81° W in the cutoff-momentum interval 0.4–3 GeV/c agrees with the theoretical spectral shape calculated in the manner of Barrett *et al.*

I. INTRODUCTION

The investigation of muon intensity at large zenith angles is necessary for the study of spectral shape in cosmic-ray phenomenology and of geomagnetic effects on muons. Only a few experiments[1-6] have been performed measuring the absolute low-energy muon intensity at large zenith angles. No absolute muon intensity data at large zenith angles above 0.4 GeV/c is available near the geomagnetic equator. The present paper reports the measurement of the absolute muon intensity at axial zenith angles 75°W and 81°W, in the cutoff-momentum interval 0.4–3 GeV/c, near the geomagnetic equator (12°N geomagnetic latitude), using a flash-tube range spectrograph. The angular distribution of muons has been studied and the experimental muon spectrum has been compared with the theoretical spectrum calculated in the manner of Ashton *et al.*[7]

II. THE EXPERIMENT

The sea-level muon flux at zenith angles 75°–85°W at Calcutta (vertical cutoff rigidity of primaries P_c =16.5 GV, 24 m above sea level) has been measured by an integral range spectrograph. The schematic diagram of the experimental setup is illustrated in Fig. 1. The zenith-angle range was ±4.6° about the axis of the telescope. The lead absorbers were placed between the detectors C_1 and C_3. The total thickness of the absorbers was varied from 237 to 2168 g cm^{-2} of lead-equivalent material. The particle-selection system consisted of Geiger counter trays $C_1C_2C_3$, which defined the trajectories of the accepted particles, and the three anticoincidence trays AC_1, each placed below 5 cm lead, which helped reduce the frequency of contaminating air shower events. The flash tubes and the detector system were of a type described in our recent papers.[8]

The charged-particle detection efficiency of the counter telescope is about 98%. The sensitive dimension of each beam defining counter is 30× 3 cm^2, estimated by applying the method of Greisen and Nereson,[9] and the acceptance of the range spectrograph, defined by the trays C_1 and C_3, each with a sensitive area 30× 15 cm^2, has been estimated by using the procedure of Flint *et al.*[5] for different effective zenith angles and is presented in Table I. A threefold coincidence pulse from the counter trays, triggered by the passage of a charged particle through the spectrograph, flashed the neon-tube hodoscope stacks F_1 and F_2 and

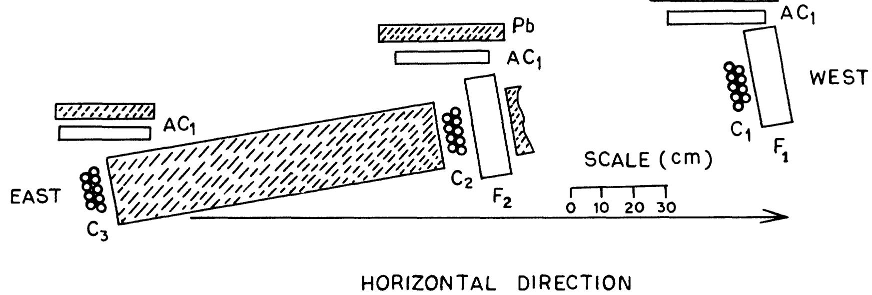

FIG. 1. Schematic diagram of the experimental arrangement.

TABLE I. The muon intensity at different zenith angles above 0.4 GeV/c.

Zenith angle Axial	Zenith angle Effective	Aperture (cm^2 sr)	Run time (h)	Observed No. of particles (singles +knock-on)	Corrected No. of particles	Absolute muon intensity per 10^4 cm^2 sec sr
75°W	74.5°W	4.97	81	668 +35	718	4.95 ± 0.19
81°W	80.3°W	4.82	100	324 +15	346	1.99 ± 0.11
85°W	84.1°W	4.76	131	135 +8	146	0.65 ± 0.05

caused the event to be photographed. These photographs exhibit the nature of the particle track, whether single penetrating or accompanied by other particles detected by the coincidence *cum* anticoincidence of Geiger trays $C_1C_2C_3$-AC_1. The small extensive showers were visually rejected and the muon rate for different ranges of muons has been estimated.

The ranges of the detected muons were converted into momenta using the method of Serre.[10] The scattering correction to the muon ranges due to zigzag motion is estimated after Koenig.[11] In the range interval 237–2168 g cm^{-2} of lead, this correction increased the actual muon ranges by 1.98% to 1.10%.

The effective working time of the detector system has been calculated from the operating time of the apparatus, taking into account the dead time introduced by the cycling operation and the quenching pulse applied to the counters.

III. RESULTS AND DISCUSSION

The range spectrograph has been operated at zenith angles 75°, 81°, and 85° in the western azimuth. The total run time for each particular ori-

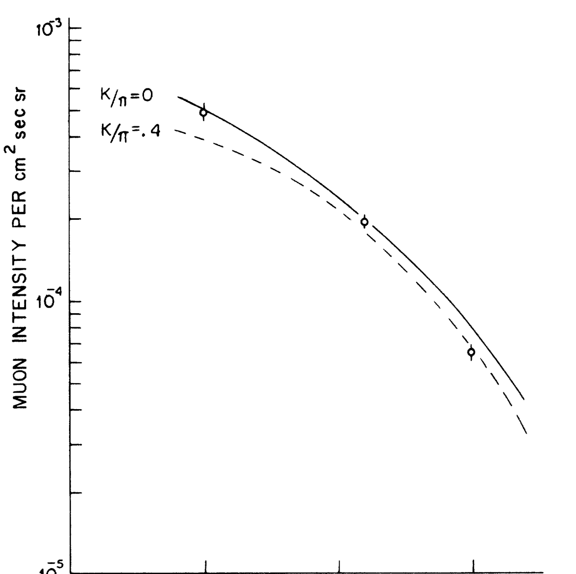

FIG. 2. The variation of absolute integral muon intensity with axial zenith angle. The solid and broken curves are obtained from the differential spectra in the manner of Ashton *et al.* (Ref. 7) for $K/\pi = 0$ and 0.4, respectively. Experimental results are denoted by open circles.

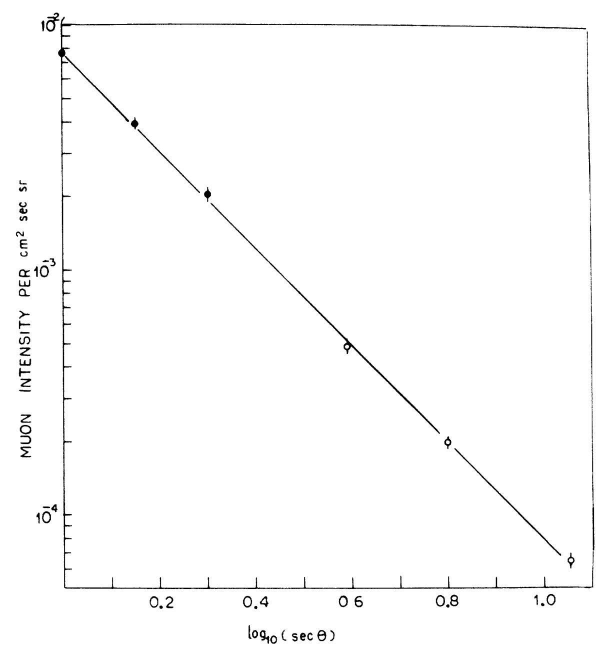

FIG. 3. Angular distribution of muons of momenta above 0.4 GeV/c. Solid circles indicate the previous work of Bhattacharyya (Refs. 13 and 14) corrected to include "knock-on" events; open circles indicate present work.

TABLE II. Integral muon spectrum at axial zenith angle 81°W.

Cutoff momentum	Run time (h)	Observed No. of events (singles + knock-on)	Corrected No. of events	Absolute integral muon intensity per 10^4 cm^2 sec sr
1.0	117	304 + 22	335	1.65 ± 0.09
1.5	144	331 + 25	366	1.46 ± 0.08
2.0	100	203 + 16	226	1.30 ± 0.09
3.0	112	154 + 15	176	0.91 ± 0.07

entation of the telescope axis was about 81, 573, and 131 hours, respectively. The photographs containing the penetrating particles (including single penetrating particles and also single penetrating particles accompanied by knock-on events) have been scanned for the evaluation of the absolute muon intensity. The scattering corrections have been estimated by using Germain's[12] procedure and the calculated net number of muons scattered out of the acceptance of the detector changes from 0.1–2% of the observed integral intensity in the momentum interval 0.4–3 GeV/c. Table I shows the observed and corrected integral muon intensity above 0.4 GeV/c in the zenith-angle interval 75°–85°W.

The integral muon spectra at large zenith angles is calculated by integrating the theoretical differential muon spectrum of Ashton *et al.*[7] from 0.4 GeV/c for $K/\pi = 0$ and $K/\pi = 0.4$, and both spectra are plotted in Fig. 2, along with the present experimental results. It is found from Fig. 2 that the muon intensity above 0.4 GeV/c agrees with the calculated curves for axial zenith angles 75°W and 81°W for $K/\pi = 0$, but at 85°W the curve for $K/\pi = 0.4$ is more in accordance with the experimental results. This fact indicates that the contribution of muons from kaon parentage is higher for the muons reaching the earth at very large zenith angles (~85 °). Moreover, the angular distribution of muons above 0.4 GeV/c at large zenith angles near the equator follows the trends predicted by Ashton *et al.*[7]

The integral muon intensity can also be expressed as $I(\theta) = I(0)\cos^n\theta$, where $I(\theta)$ is the intensity at zenith angle θ, $I(0)$ is the vertical muon intensity, and n is a function of muon momentum. Figure 3 shows the angular distribution of penetrating particles for cutoff momentum of 0.4 GeV/c. The experimental data, including all penetrating particles and knock-on events at axial zenith angles 0°, 45°W, and 60°W, published in our previous reports,[13,14] are presented in Fig. 3 along with the present results. The value of the cosine exponent n obtained from the linear regression analysis applied to the data comes out to be $n = 1.98^{+0.07}_{-0.03}$, which agrees with the results of Sreekantan *et al.*[15] and Kim *et al.*[16] This fact indicates that the expected variation in angular intensity of muons follows a cosine-square law and is valid up to a zenith angle 85°W in the cutoff momentum region 0.4–3 GeV/c.

The absolute integral muon spectrum at axial zenith angle 81°W has been measured in the cutoff-momentum range 1–3 GeV/c and is summarized in Table II.

The spectrum of single muons previously reported[13,14] has been corrected for knock-on electron events in the present work and the total absolute muon spectra at the axial zenith angles 0°, 45°W, and 60°W are shown in Fig. 4 along with the present results at 81°W. The phenomenological form taken after Barrett *et al.*[17] and modified by Allkofer (private communication) has been used to evaluate the sea-level muon spectra at different zenith angles, assuming a cosine-square angular distribution of muon intensity. Only the pion parentage has been considered. The integral sea-level muon in-

TABLE III. The value of the exponent γ at different muon momenta.

Muon momentum (GeV/c)	0.4	1.0	1.5	2.0	3.0
γ	0.14 ± 0.03	0.36 ± 0.04	0.51 ± 0.05	0.64 ± 0.06	0.86 ± 0.07

tensity has been estimated using the relation

$$N(\geq E_\mu) = \int_{E_\mu}^{\infty} W_\mu A(E_\mu + 2.04)^{-\gamma} \frac{r_\pi^{\gamma-1} B_\pi \cos^n\theta}{(E_\mu + 2.04 + B_\pi)} dE_\mu , \quad (1)$$

where $B_\pi = 90$ GeV and $r_\pi = 0.76$. The probability of muons, produced at a vertical depth 100 g cm^{-2}, surviving to a sea-level depth of 1033 g cm^{-2}, with muon energy E_μ, is given by Rossi[18] as

$$W_\mu = \left(\frac{0.097E_\mu}{E_\mu + 2.04}\right)^{1.1/(E_\mu + 2.28)} . \quad (2)$$

The unknown parameters A and γ are fitted to the experimental data by using the maximum likelihood technique, and the best fit vertical and slant muon spectrum thus obtained yields $A = 0.18 \pm 0.02$ for the different values of γ presented in Table III.

The calculated muon spectra at axial zenith angles 0°, 45°, 60°, and 81° are shown in Fig. 4. The approximate agreement of the experimental results with the theoretical values has been observed up to zenith angle 60°, but a deviation is found at 81° above 1.5 GeV/c. This may be due to the kaon contribution to the integral flux of muons reaching earth at large zenith angles.

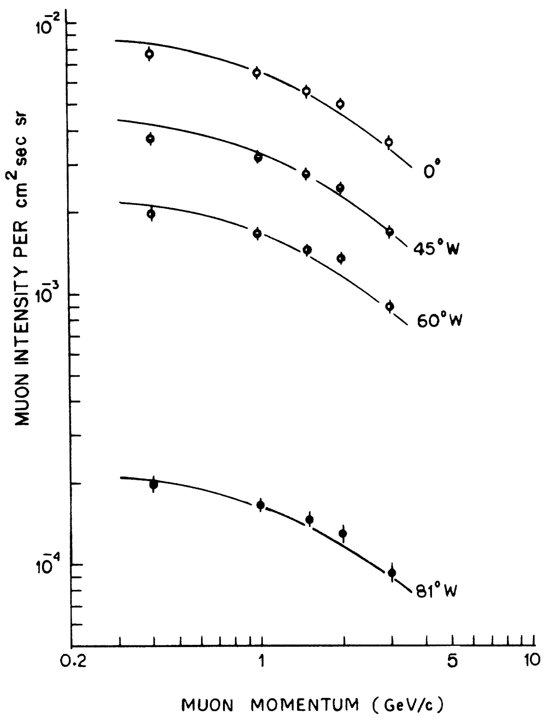

FIG. 4. Absolute sea-level integral muon spectra at different zenith angles: ○, 0°; ◒, 45°W; ◑, 60°W; and ●, 81°W. Solid lines are the theoretical curves.

IV. CONCLUSION

The angular distribution of the low-momentum sea-level muon intensity (above 0.4 GeV/c) at large zenith angles in the western azimuth direction follows the zero distribution

$$I(\theta) = I(0)\cos^n\theta, \quad n = 1.98^{+0.07}_{-0.03}$$

and agrees with the spectral shape expected by Ashton *et al.*[7] for $K/\pi = 0$ at 75° and 81°, and $K/\pi = 0.4$ for the intensity at zenith angle 85°.

The measured muon spectrum at 81°W in the cutoff momentum interval (0.4–3 GeV/c) agrees approximately with the theoretical spectral shape calculated from Barrett *et al.* The result indicates that the kaon contribution to the integral flux of muons increases with zenith angle.

ACKNOWLEDGMENTS

The author expresses his thanks to Professor D. Basu, Director, Indian Association for the Cultivation of Science, for his encouragement and to Professor R. L. Sen Gupta, Principal, Presidency College, Calcutta, for laboratory facilities. Thanks are due to the University Grants Commission, Government of India, for financial support.

*Also at Department of Physics, Jadavpur University, Calcutta-700032, India.

[1] D. Jakeman, Can. J. Phys. 34, 432 (1956).
[2] B. G. Wilson, Can. J. Phys. 37, 19 (1959).
[3] R. J. R. Judge and W. F Nash, Nuovo Cimento 35, 1025 (1965).
[4] J. N. Crookes and B. C. Rastin, Nucl. Phys. B 39, 493 (1972).
[5] R. W. Flint, R. B. Hicks, and S. Standil, Can. J. Phys. 50, 843 (1972).
[6] N. L. Karmakar, A. Paul, and N. Chaudhuri, Nuovo Cimento 17B, 173 (1973).
[7] F. Ashton, Y. Kamiya, P. K. Mackeown, J. L. Osborne, J. B. M. Pattison, P. V. Ramana Murthy, and A. W. Wolfendale, Proc. Phys. Soc. 87, 79 (1966).
[8] D. P. Bhattacharyya, Z. Phys. 234, 17 (1970); Nucl. Instrum. Methods 118, 289 (1974).
[9] K. Greisen and N. Nereson, Phys. Rev. 62, 316 (1942).
[10] C. Serre, CERN Report No. 67-5, 1967 (unpublished).
[11] H. P. Koenig, Phys. Rev. 69, 590 (1946).
[12] L. S. Germain, Ph.D. thesis, University of California, Berkeley, 1949 (unpublished); Phys. Rev. 80, 616 (1950).
[13] D. P. Bhattacharyya, J. Phys. A 6, 582 (1973).
[14] D. P. Bhattacharyya, Nuovo Cimento 24B, 78 (1974).

[15]B. V. Sreekantan, S. Naranen, and P. V. Ramana Murthy, Proc. Indian Acad. Sci. 53, 113 (1956).
[16]Y. S. Kim and L. Voyvodic, Nuovo Cimento 66B, 183 (1970).
[17]P. H. Barrett, L. M. Bollinger, G. Cocconi, Y. Eisenberg, and K. Greisen, Rev. Mod. Phys. 24, 133 (1952).
[18]B. Rossi, *High Energy Particles* (Prentice Hall, New York, 1952, p. 157.