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Absolute differential sea level muon spectra at zenith angles 45° W and 60° W near the geomagnetic equator

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Abstract. The absolute sea level differential cosmic muon spectra at zenith angles 45° and 60° in the western azimuth have been determined near the geomagnetic equator (at 12° N) by using the range spectrograph in the momentum interval 0·5–3 GeV/c. The experimental muon spectra after corrections agree well with the spectra, calculated after Jabs theory for the same location, above muon momentum 1·8 GeV/c. The results have been compared with others obtained at higher latitudes. It is found that the variation of differential muon intensity with lg sec θ (θ is the zenith angle of the spectrograph axis) diminishes slowly with the increase of muon momentum from 1 to 3 GeV/c. The variation of the cosine exponent in the expression $I(\theta) = I(0) \cos^n\theta$ agrees with that calculated after Jabs. The present spectra after latitude corrections for 55°N agree well with that magnetic spectrograph result of Allkofer and Andresen for the same latitude at 45° W and with that of Judge and Nash for 60° W.

1. Introduction

The study of absolute cosmic muon spectra at different zenith angles is necessary to investigate the influence of the earth's magnetic field on penetrating cosmic rays and for an estimate of the composition of the parents of muons and their production processes. For inclined directions the atmospheric depth changes and consequently the muon spectra also change. The reduction of the inclined muon intensity occurs at low energy due to the increase of atmospheric depth which gives a greater decay probability for muons.

A small number of high latitude experiments on the determination of the absolute muon spectra at zenith angles 45° W and 60° W have been performed by several authors. Moroney and Parry (1954, to be referred to as MP) measured the inclined muon spectrum at 60° W using the Melbourne magnetic spectrograph. The muon spectrum in reference MP at 60° agrees with the experimental spectrum determined later at 68° by the Cornell group (Pak *et al* 1961). Later Coates and Nash (1962, to be referred to as CN) determined the muon spectrum at 45° W for muon momenta in the range 0·8 to 40 GeV/c. There exists an appreciable disagreement between the spectra determined by these authors and Allkofer and Andresen (1967, to be referred to as AA), for the same zenith angles, below 3 GeV/c. The magnetic spectrograph measurements of Judge and Nash (1965, to be referred to as JN) and Allkofer and Clausen (1970, to be referred to as AC) at 60° W exceed appreciably the spectrum of MP in the momentum region 0·85–3 GeV/c.

The present paper reports a direct measurement of the absolute sea level muon spectra at zenith angles 45° and 60° western azimuth in the momentum range 0·5–3 GeV/c near the geomagnetic equator by using a flash-tube range spectrograph in which the momentum of muons has been evaluated from the residual range of the penetrating particles. The experimental spectra after scattering and other corrections have been compared with the high latitude spectra of the authors MP, CN, AA, JN and AC. No comparable data on the muon spectra at zenith angles 45° and 60° are available near the geomagnetic equator. The present muon spectra have been compared with the theoretical spectra calculated after Jabs (1967). The variation of differential muon intensity with $\lg \sec \theta$ at different momenta has been studied. The change of cosine exponent of the muon spectrum has also been compared with the values expected after theory.

Finally, the latitude corrections have been applied to our spectra by using Jabs' theory to estimate the high latitude spectra and the comparison of our latitude corrected spectra with the recent high latitude spectra of different authors has been displayed in figure 7.

2. The experiment

The cosmic muon spectra in the zenith angles 45° and 60° western azimuth at Calcutta (80 ft above sea level, 12° N geomagnetic latitude) have been measured by a differential range spectrograph in the momentum range 0·5–3 GeV/c in two sets of experiments. Figure 1 shows the schematic layout of the flash-tube range spectrograph. The experiment has been performed with lead absorbers Σ and T, placed within the detectors. The penetrating cosmic muons of different momenta have been allowed to traverse the materials Σ and T and finally stopped in a layer of 134 g cm^{-2} of lead. Two neon flash-tube stacks, each containing of an array of nine layers of flash tubes, have been used for the location of the penetrating particles. The selection system consisted of Geiger counter trays C_1, C_2, C_3 which defined the trajectories of the accepted particles and two counter trays AC_1, AC_2 which were connected in anti-coincidence and acted so as to reduce the frequency of air showers triggering the arrangement and to notice the stopping of the particle in the differential layer D of 134 g cm^{-2} of lead. The anti-coincidence

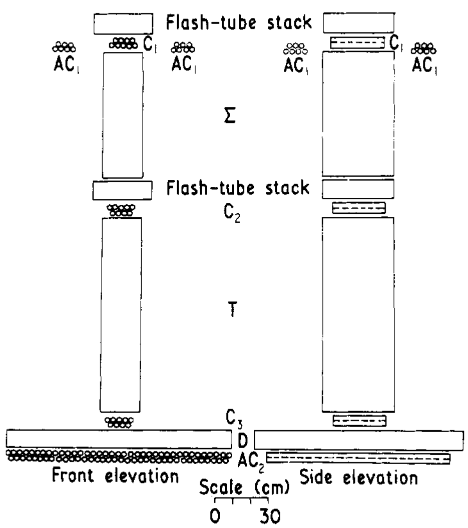

Figure 1. Schematic diagram of the experimental set up.

counter tray AC_2 covered more than the solid angle defined by about 75° semi-vertical cone from the lowest counter geometry. The flash tubes and GM counters used in this experiment are of the type described in our previous work (Bhattacharyya 1973). The muon telescope efficiency is 99 %. The sensitive dimension of each beam defining counters is $30 \times (3{\cdot}0 \pm 0{\cdot}2)\ cm^2$ determined by the method of Greisen and Nereson (1942) and the acceptance of the spectrograph, defined by the Geiger trays C_1 and C_3, has been found to be $5{\cdot}00 \pm 0{\cdot}13\ cm^2$ sr. The particle trajectories defined by the two arrays of flash tubes were photographed by a camera.

The ranges of muons corresponding to different absorber thicknesses have been converted into momenta by using the theory of Serre (1967). The effective ranges have been corrected for the zig-zag motion of the particle due to Coulomb scattering by using the method of Koenig (1946), and for this effect the experimental range value is about 5 % less than the theoretical value of Serre in the muon momentum interval 0·5–3 GeV/c. The straggling correction of the particle has been neglected.

The air showers have been partially eliminated by the GM trays AC_1 as shown in figure 1.

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

3. Results and discussion

The flash-tube range spectrograph has been operated at zenith angles 45° and 60° in the western azimuth. The total operating times for each particular orientation of the apparatus at 45° and 60° west are about 933 and 1188 hours, respectively. The photographs that record the nature of GM coincidences have been divided into three categories: (i) those containing single penetrating particles only, (ii) those showing incident penetrating particles accompanied by other particles, and (iii) those which do not show a single particle unambiguously because of accidental coincidences; these showers cause the majority of the flash-tubes to glow. Type (iii) events make up about 2 % of the total number of single events detected. The ratio of the intensity of accompanied to the differential intensity of single penetrating (presumably muons) particles is plotted as a function of muon momentum in figure 2 for the two zenith angles 45° W and 60° W. It is evident from the plot that the ratio of accompanying to single particles increases with muon momentum and this ratio is almost the same in these two zenith angle experiments. This fact suggests that the frequency of shower particles remains the same for a small variation of zenith angle and the same energy transfer of mono-energetic muons.

3.1. Correction factors

The correction factors applied to the observed data are because of (i) the inefficiency of the particle telescope, (ii) the scattering loss of particles through the absorber layers Σ and T, (iii) the scattering out of particles through the differential layer D (figure 1) whose momenta exceed those corresponding to the differential layer. The proton contribution is neglected since the data on the proton spectrum at the inclined direction are not available up until now. The correction (i) is 1 %, (ii) is positive and (iii) is negative with respect to the observed data. Muons that are going to stop in the layer D must have relatively low momenta when passing through the absorber above the counter tray C_3. Some

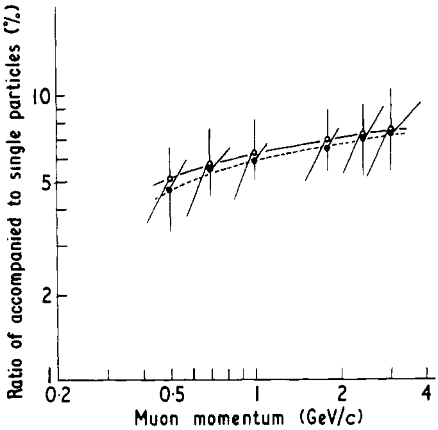

Figure 2. The ratio of the intensity of accompanying particles to the intensity of single particles as a function of muon momentum. The present work: ● at $\theta = 45°$ W and ○ at $\theta = 60°$ W.

particles which have passed through C_1, and are travelling in such a direction that they should hit Geiger trays C_2 and C_3, might be scattered away (in layers Σ and T) from C_2 and C_3. This effect is largely compensated by the particles which are scattered in such a direction that they hit tray C_3 when they would not have done so if there had been no scattering. The other scattering effect may cause particles to be gained. The particles emerging from the counter tray C_3 of high momenta that can penetrate layer D but are scattered out from the anticoincidence tray AC_2 are counted but are unwanted, and so these numbers have to be subtracted from the observed number of particles. The scattering corrections have been estimated by following Germain's (1949) procedure and the percentage of particles scattered in and out has been calculated for zenith angles 45° W and 60° W. The correction (ii) in layers Σ and T ranges from 2·53 to 28·5% in the momentum region 0·5 to 3 GeV/*c* and is positive to the observed data. In layer D for the same momentum interval the correction (iii) changes from −19 to −16% for 45° W and from −28·2 to −17% for 60° W. The corrected absolute differential intensity of single muons at the zenith angles 45° W and 60° W have been plotted in figure 3 in the momentum range 0·5–3 GeV/*c*.

3.2. Theoretical spectra

The sea level muon spectrum at a zenith angle θ has been calculated from the spectrum of primary protons by using the theory of Jabs (1967). The pions decay into muons with a constant energy degradation factor 0·76. After consideration of the survival probability of muons from the production depth y and ionization loss throughout the atmosphere, the sea level muon spectrum $I(E_\mu, \theta)$ at zenith angle θ after Jabs comes out to be of the form

$$I(E_\mu, \theta)\, dE_\mu = K \int_0^{y_0} [E_\mu + (y_0 - y) \sec\theta\, E']^{(-\gamma+2n)/(1-n)} \exp\left(-\frac{y}{\lambda}\sec\theta\right) \times \left(\frac{yE_\mu}{y_0[E_\mu + (y_0 - y)\sec\theta\, E']}\right)^{a\sec\theta/(E_\mu + y_0 \sec\theta\, E')} \sec\theta\, dy\, dE_\mu$$

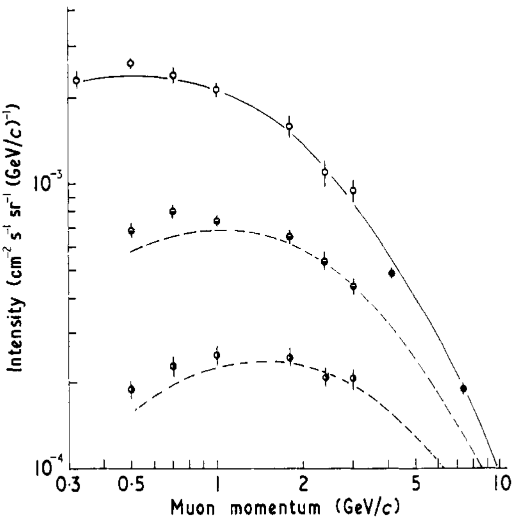

Figure 3. The absolute sea level differential muon spectra of the PW together with the calculated results after Jabs' theory. Experimental points and theoretical curves at zenith angles 0°, ○ (● Dau 1968 at $\theta = 0°$ for 9° N) and full curve, 45° W, ◒ and broken curve, and 60° W, ◑ and chain curve are shown.

where the constant energy loss of muons per g cm^{-2} of air, $E' = 2{\cdot}2$ MeV;

$$a = Hm_\mu c^2/cT \simeq 1{\cdot}1;$$

the scale height of the atmosphere, $H = 7{\cdot}02$ km; muon rest mass, $m_\mu c^2 = 107$ MeV; the velocity of light, $c = 3 \times 10^{10}$ cm s^{-1}; the lifetime of the muon, $T = 2{\cdot}15$ μs; the exponent of the primary spectrum has been taken from our previous work (Bhattacharyya 1972), $\gamma = 2{\cdot}65$; the exponent of meson multiplicity, $n = 0{\cdot}25$; the attenuation length of protons in air, $\lambda = 120$ g cm^{-2}; the sea level atmospheric depth $y_0 = 1033$ g cm^{-2} of air. The above integral was solved by numerical integration and calibrated with the vertical muon spectrum (Bhattacharyya 1970, Dau 1968). The calculated theoretical curves for zenith angles 45° and 60° have been plotted in figure 3. The present low latitude inclined muon spectra at zenith angles 45° and 60° W (to be referred to as PW) agree well with the calculated spectra for muon momenta above 1·8 GeV/c. It is evident from the plot that the trend of the spectrum with increasing zenith angle is extended in nature. So a hardening of the spectrum appears, ie the flatness of the spectrum, due to the increased loss by decay of the low momentum mesons in travelling greater distances from the production layer.

Figure 4 shows the ratio of the muon intensity determined by various authors to the PW as a function of muon momentum. The muon spectra determined by CN at 45° W lie below PW by about a factor 0·88–0·91 the limits of our statistical fluctuations (shaded area) in the momentum range 0·7–3 GeV/c. The spectrum of AA lies above PW by a factor 1·4–1·15 in the range 0·5–3 GeV/c. The muon spectra at 60° W determined by JN and AC around 55° N latitude and that of MP at latitude 50° S have been compared with PW in the same figure (figure 4). The work of AC exceeds PW by a factor 2·15–1·05 in the interval 0·5–3 GeV/c. The spectrum of JN exceeds PW by a factor of 1·43–1·05 in the investigated range 0·9–3 GeV/c. The muon spectrum of the Melbourne group MP agrees approximately with PW by a factor 1·15–0·84 in the range 0·7–3 GeV/c. The sea level

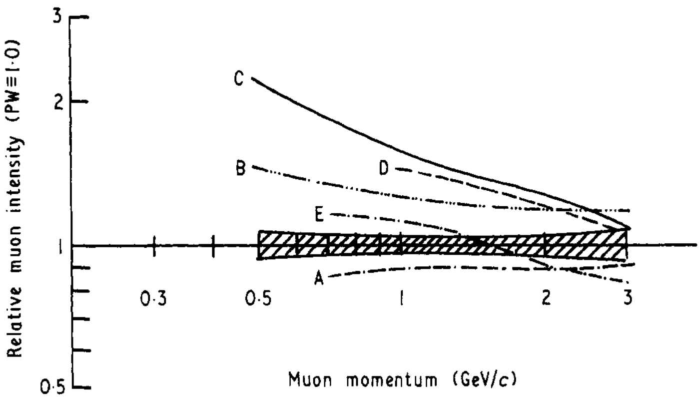

Figure 4. The ratio of the muon intensity determined by different authors to PW as a function of muon momentum: curve A, CN, and curve B, AA, at 45° W; curve C, AC, curve D, JN and curve E, MP, at 60° W.

muon intensity varies with the following parameters (i) geomagnetic latitude, (ii) solar activity, (iii) meteorological conditions, (iv) systematic errors in the measurements which include the inefficiency of the muon telescope due to end effects and the loss of particles due to multiple scattering and dead time of the detector. In our case the scattering of the particles in and out of the absorbers $\Sigma + T$ and D leads to additional errors in the measurements. The uncertainties in the method of corrections for muon scattering and the aperture determination are 2 and 2·6 % respectively. After these corrections the PW lie below the recent high latitude precision measurements of AA at 45° W and of AC and JN at 60° W and this discrepancy is mainly due to the geomagnetic latitude effect of cosmic muons, since the latitude effect is significant below 3 GeV/c. The track visualizer measurements also involve a bias of rigorous rejection of accompanying events due to which the single muon intensity varies with different experiments. The correction for knock-on events generally enhances the experimental single muon spectra by 4–10 %. The rejection of accompanying events in the anti-coincidence method is essential since a high energy muon after a certain energy transfer counted by the spectrograph for its lower specific residual range causes the admixture of the particles in the spectrum energy region. Moreover the anti-coincidence method is more reliable in the measurements of absolute differential muon intensity than the coincidence technique since it reduces the fluctuations in cosmic ray intensity due to the time variations and statistical uncertainty of the counting rates.

3.3. Intensity of muons as a function of zenith angles

The differential muon intensity can 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 intensity of muons and n is a function of muon momentum. The above relation can be expressed as

$$\lg I(\theta) = \lg I(0) + n \lg(\sec\theta)^{-1}.$$

Using the data of our earlier work for the vertical muon spectrum and PW at $\theta = 45°$ W and 60° W, the differential muon intensity has been plotted as a function of $\lg\sec\theta$ in figure 5 from muon momentum 1 GeV/c upwards. The gradients of the least square fit straight lines in the plot correspond to the values of n at the various momenta. Table 1

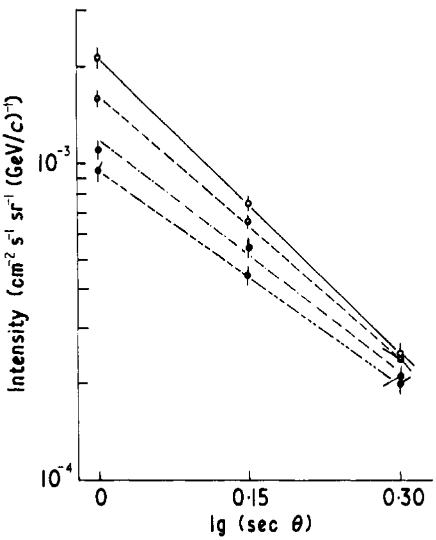

Figure 5. The variation of differential muon intensity with lg sec θ in the western azimuth: ○, ⊖, ◑ and ● represent the intensity at the muon momenta 1, 1·8, 2·4 and 3 GeV/c respectively.

shows the values of n obtained from the plot with the results of MP and JN. It is evident from the plot (figure 5) that the gradient value n decreases with the increase of muon momentum.

Table 1

Muon momentum (GeV/c)	Cosine exponent n in the western azimuth			
	Present Work $\theta = 45°$	$\theta = 60°$	Judge and Nash (1965)	Moroney and Parry (1954)
1·0	3·03 ± 0·26	3·08 ± 0·17	2·64 ± 0·11	3·05
1·8	2·56 ± 0·28	2·71 ± 0·16	—	—
2·4	2·01 ± 0·39	2·37 ± 0·21	—	—
3·0	2·14 ± 0·37	2·17 ± 0·18	—	2·15

3.4. Theoretical aspects of the cosine exponent

The theoretical values of the cosine exponent n have been calculated after Jabs' (1967) theory and have been plotted as a function of sea level muon momentum in figure 6 along with the experimental points of PW. The experimental results agree well with the values calculated after Jabs for muon momenta above 1 GeV/c. It is evident from the plot that the intensity of high momentum muons increases appreciably with zenith angles.

3.5. Latitude corrections of the PW for the determination of the muon spectra at 55° N geomagnetic latitude

A study has been made to interpret the major difference between PW and the high latitude recent results obtained by the authors AA, JN and AC in terms of geomagnetic

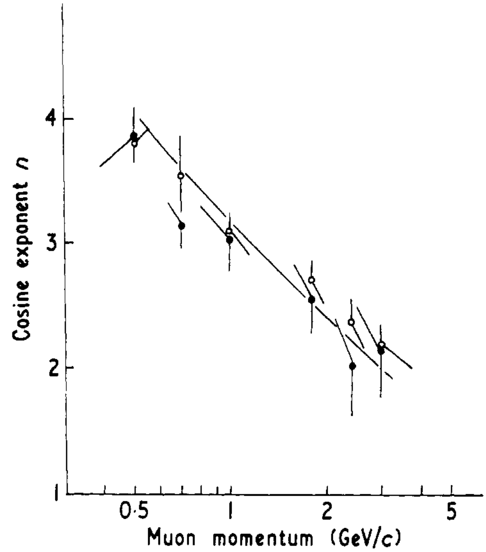

Figure 6. The cosine exponent *n* expressed as a function of muon momentum. The present work: ● at 45° W; ○ at 60° W. The curve represents the calculated values after the theory of Jabs (1967).

effects on cosmic muons by using the theory of Jabs (1967). Figure 7 shows the present muon spectra corrected for latitude effect after Jabs' theory along with the magnetic spectrograph data of AA, JN and AC. Our results agree well with that of AA for 45° W and with JN for 60° W data. The theoretical curves after Jabs' theory for high latitude (55° N) at zenith angles 45° and 60° have been displayed in the same figure and are corrected for scattering of muons in the atmosphere. These theoretical spectra have been calculated on the basis of zenith angles but not on the basis of east–west asymmetry of

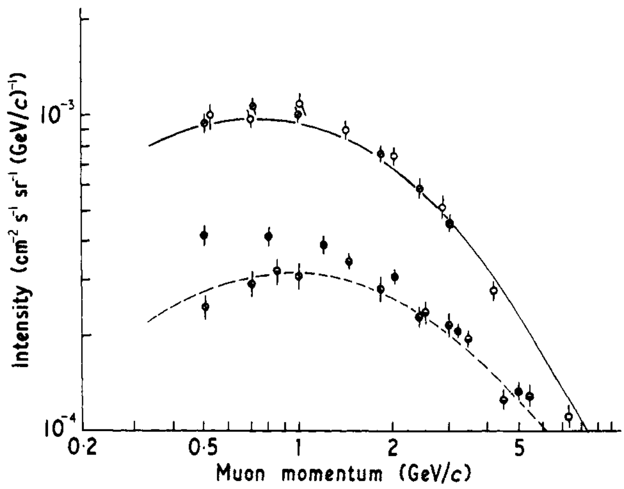

Figure 7. The high latitude muon spectra at different zenith angles. Data for 45° W: ○, AA; ⊘, corrected PW; full curve, theoretical curve; for 60° W: ●, AC; ◒, JN; ⊗, corrected PW; broken curve, theoretical curve.

muon intensity. Thus the above plot indicates that the geomagnetic latitude effect of muon intensity can explain the major deviation of our low latitude inclined muon spectra from the Nottingham spectrum of JN and Kiel spectra of AA, AC.

4. Conclusion

The absolute sea level differential muon spectra at the zenith angles 45° and 60° western azimuth give the spectral shape of the low momentum sea level muon intensity in the equatorial region in the investigated momentum range 0·5–3 GeV/c. The flash-tube range spectrograph at an inclined direction has been operated for the first time near the equatorial region. The present experimental muon spectra at the two zenith angles agree well with those calculated after Jabs' theory for the same location above 1·8 GeV/c. In the present study the cosine exponent of the inclined muon intensity decreases with increasing muon momentum and exhibits a hardening in the spectrum, this exponent agrees with the theoretical values after Jabs. Finally the PW has been corrected for the geomagnetic effect of muons by using Jabs' theory for 55° N geomagnetic latitude and these results are also in agreement with the magnetic spectrograph results of AA for 45° W and with JN for 60° W.

Acknowledgments

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