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The muon flux of cosmic rays at sea level

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Abstract. The sea-level absolute vertical integral cosmic ray muon intensities for three momenta near 1 GeV/c at 12°N were measured with a range spectrometer. The results obtained from this measurement are used to derive the intensities at a latitude of 50°N by applying the latitude correction suggested by Olbert. The integral muon intensities are found to be on the average 3·5 % lower and 21·6 % higher than the values obtained by Allkofer *et al* and Rossi respectively. The differential intensities derived from the integral ones are 20 % higher than those calculated from Olbert at the same latitude. The results of the other recent measurements on the differential muon intensities in the low energy region in relation to a form spectrum presented by us, are also discussed.

1. Introduction

Recent measurements (Allkofer *et al* 1970a, b, 1971, Bateman *et al* 1971, Crookes and Rastin 1971a, b, De *et al* 1971, Ayre *et al* 1971) of the absolute muon intensity at sea level by different workers indicate that the muon intensities are somewhat higher than the previously accepted values (Greisen 1942, Rossi 1948, Kraushaar 1949, Pomerantz 1949). According to York (1952) the discrepancy could be attributed to the fact that the Greisen value had not been properly corrected for the loss of particles out of the geometry of the apparatus due to the multiple Coulomb scattering in the absorber. Again according to Allkofer *et al* the discrepancy may be due to the fact that the Greisen intensity was not corrected for the zig-zag motion of the particles due to the multiple scattering which results in a shift in momentum and hence in an increase in intensity.

Only a few experiments (Fukui *et al* 1957, Subramanian *et al* 1958, Allkofer *et al* 1968, Bhattacharyya 1970) have so far been performed at low latitudes. The results obtained are more or less in agreement with those of Rossi (1948) after the geomagnetic latitude effect, as reported by Olbert (1954), has been taken into consideration. An experiment has been performed at 12°N at sea level in order to investigate whether there is an increase in intensity at low geomagnetic latitudes. Such an increase in muon intensity has already been reported by the present authors although this was only a preliminary communication (De *et al* 1971).

2. The experiment and procedure

Figure 1 shows the geometrical arrangement of the apparatus which is similar to that of Allkofer *et al* (1970). Two trays of crossed Geiger–Müller counters A and B, each with a sensitive area of $7{\cdot}3 \times 7{\cdot}3\ \mathrm{cm}^2$, form a telescope with a geometric acceptance of

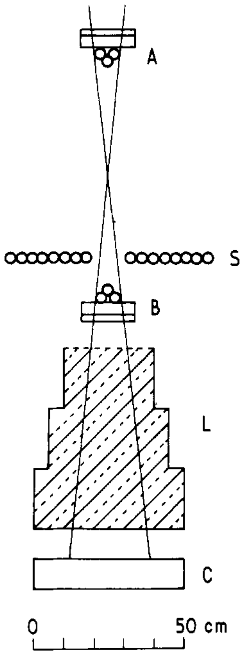

Figure 1. Front view of the apparatus; A, B crossed Geiger counter arrays, S Geiger counter shower tray, L lead absorber, C scintillator.

0·4 cm^2 sr. The small acceptance angle selects only the paraxial rays. The efficiency of the counters over the sensitive region, determined precisely by Fenyves' (1955) method, was found to be 99·8 %. Below these beam defining counters, there is a lead absorber of accurately known thickness to impose the lower momentum cut off. Under this arrangement is placed a plastic scintillation counter C. A ring S of four trays of Geiger counters has been arranged around the telescope to account for the EAS events. By simultaneous registration of counts n_{ABC} and n_{ABCS}, the actual integral rate can be determined.

The exact muon rates are given by

$$n_{ABC\bar{S}} = n_{ABC} - K_1(n_{ABCS} - K_2 n_{ABC}). \tag{1}$$

Here $K_1 = 1{\cdot}3 \pm 0{\cdot}13$ is the same as the value used by Allkofer *et al* (1970) as the S counters of our experimental arrangement are of exactly the same size as those of the above reference. The factor K_2 takes into account those single muons which produce knock-on electrons and hence are detected as showers. This was calculated to be 0·031 from the knock-on electron probability given by Bhabha (1938) for muon momentum greater than 1 GeV/c, energy transfer greater than 5 MeV and effective target thickness 3 mm iron between the counter trays A and B.

All the rates have been corrected for the efficiency of the detectors, scattering and proton contributions.

The correction for loss of particles due to multiple scattering has been accomplished by following the procedure of Sternheimer (1954) using the distribution function of Eyges (1948) which includes the effect of energy loss in the absorber. The probability P that a particle passing through the counters A and B would be found at a distance s

from the straight through position at counter C can be expressed as

$$P = \frac{1}{\pi r_0^2} \exp\left(\frac{-s^2}{r_0^2}\right) \tag{2}$$

where $r_0 = 2(A_2 + 2A_1 l + A_0 l^2)^{1/2}$. A_0, A_1 and A_2 are given in Eyges (1948) and l is the distance of the counter C from the lower end of the absorber. This expression is similar to that obtained by Sternheimer (1954) (equation (1)) without energy loss. Here the value of r_0 is different. If we disregard the energy loss, the expression (2) reduces to equation (1) of Sternheimer (1954).

The fraction $F(p)$ of the incident beam which passes through C after traversing A and B can then be determined for different values of momenta by extrapolating figure 4 of Sternheimer (1954). In order to deduce the value of the scattering loss correction for three integral counts ABC at three different momenta p_1, p_2 and p_3, we take the difference between any two integral counts, say between the last two of ABC counts at momenta p_2 and p_3. This gives the differential count in the momentum interval p_2 to p_3. Then the scattering loss correction for three integral counts will be respectively S_1, S_2 and S_3 times the differential counts, where S_1, S_2 and S_3 are given by

$$S_i = \frac{\int_{p_i}^{\infty} (1 - F_i(p))N(p)\,\mathrm{d}p}{\int_{p_2}^{p_3} F_2(p)N(p)\,\mathrm{d}p + \int_{p_3}^{\infty} (F_2(p) - F_3(p))N(p)\,\mathrm{d}p} \tag{3}$$

where $i = 1, 2, 3$; $N(p)\,\mathrm{d}p$ is the approximate differential muon intensity and $F_1(p)$, $F_2(p)$ and $F_3(p)$ are the fraction of particles received by C after the particles pass through the beam defining counters A and B for three different thicknesses of the absorber.

To find the momentum loss which corresponds to a certain length of the absorber the table given by Serre (1967) has been used. These Serre values have been corrected for the fact that a particle, passing through an absorber, executes a zig-zag motion due to multiple scattering. The correction in this range causes a 5 % increase in the absorber thicknesses.

3. Results and discussion

The corrected integral intensities, determined from the above experiment for three different absorber thicknesses (681·4, 792·9 and 907·2 g cm^{-2} Pb equivalent including the roof and the other materials above the apparatus) corresponding to the momenta 0·976±0·5 %, 1·130±0·5 % and 1·286±0·5 % GeV/c are given in the table 1. These integral intensities are, on average, 10 % higher than the Rossi (1948) values and 12 % lower than those of Allkofer *et al* (1970) for geomagnetic latitudes ⩾50°N. According to Olbert (1954) the present measurement at 12°N geomagnetic latitude should give 8·3 % lower integral intensity than that at 50°N latitude. To compare the present results directly with those at the higher latitudes a correction of 8·3 % was applied on the present values. This gives on the average 21·6 % higher values than those of Rossi (1948) and 3·5 % lower than those of Allkofer *et al* (1970). From this we may conclude that our results agree reasonably well with the data presented by Allkofer *et al.*

The differential intensities derived from the present integral intensities are $(2{\cdot}47 \pm 0{\cdot}41) \times 10^{-3}$ and $(2{\cdot}18 \pm 0{\cdot}39) \times 10^{-3}$ cm^{-2} sr^{-1} s^{-1} (GeV/c)$^{-1}$ at 1·05 and 1·21 GeV/c respectively. These results together with those of other workers in the low momentum region (below 10 GeV/c) have been displayed in the figure 2. Our results

Table 1. The measured rates, corrections and intensities

Momentum (GeV/c)	Event	Time (h)	Count (n)	Efficiency correction (per cent)	Corrected rate ($\times 10^{-4}$ s^{-1})	Scattering correction ($\times 10^{-4}$ s^{-1})	Proton contribution ($\times 10^{-4}$ s^{-1})	Final corrected rate ($\times 10^{-4}$ s^{-1})	Integral intensity ($\times 10^{-3}$ cm^{-2} sr^{-1} s^{-1})
0·976 ± 0·5 %	ABC	2913	29222	2·2 ± 0·15	28·48 ± 0·60 %	0·247	0·196	26·56 ± 0·18	6·64 ± 0·046
	ABCS		2459	2·3 ± 0·16	2·40 ± 2·02 %				
1·130 ± 0·5 %	ABC	2925	27665	2·2 ± 0·15	26·85 ± 0·62 %	0·308	0·184	25·04 ± 0·18	6·26 ± 0·044
	ABCS		2388	2·3 ± 0·16	2·32 ± 2·05 %				
1·286 ± 0·5 %	ABC	2907	26029	2·2 ± 0·15	25·42 ± 0·64 %	0·350	0·176	23·68 ± 0·17	5·92 ± 0·043
	ABCS		2312	2·3 ± 0·16	2·26 ± 2·09 %				

agree with Olbert's theoretical spectrum at 12°N when multiplied by a factor 1·2. These values are, on the average, 12% higher than those obtained by Bhattacharyya (1970) at the same geomagnetic latitude.

When one checks the consistency among the high latitude results one finds that the phenomenological form spectrum, presented by Allkofer *et al* (1971), does not agree well with the experimental points of the same authors in the low energy region. The following form spectrum:

$$I(p)\,dp = 3{\cdot}08 \times 10^{-3} p^{\alpha_1 + \alpha_2 \ln(p)}\,dp \tag{4}$$

where $\alpha_1 = -0{\cdot}5483$, $\alpha_2 = -0{\cdot}3977$ and p is in GeV/c, gives a better agreement (see figure 2) with the experimental results of Allkofer *et al* for momenta below 10 GeV/c. The constant $3{\cdot}08 \times 10^{-3}$ in the equation (4) refers to the muon intensity at 1·0 GeV/c given by Allkofer *et al* (1970b). This value was chosen because, as stated by Allkofer *et al* (1970b), the factor K_2 (equation (1) of this report) had been overestimated and hence the differential muon intensity at 1 GeV/c should be lower by about 5% than that presented in an earlier report (Allkofer *et al* 1970a). The experimental points of Bateman *et al* (1971) are also very close to this best fit curve, and further good agreement can be seen to exist between the experimental results obtained by the two groups. At the same time the results presented show an increase in the muon intensities in this momentum region over those measured by previous workers.

The muon intensities near 1 GeV/c reported by us at 12°N lie consistently below the present best fit curve for results at higher geomagnetic latitudes. According to

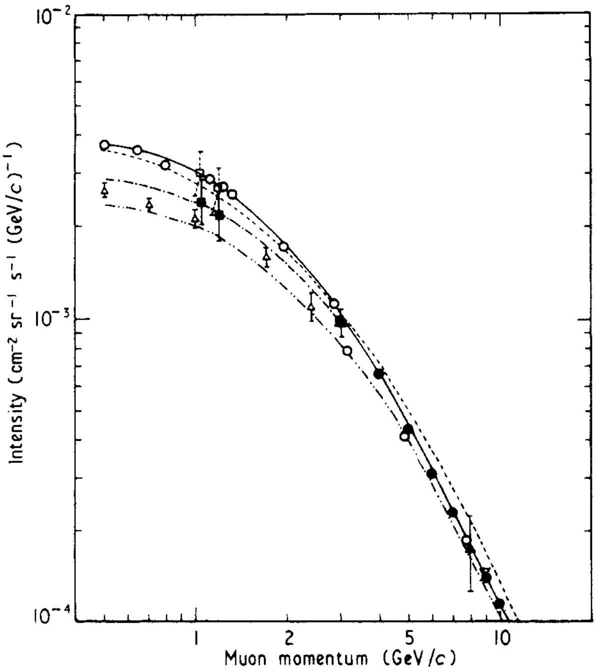

Figure 2. Recent data on the absolute vertical muon intensities. --- Allkofer *et al* (1971) best fit, — present best fit, —··— Olbert (12°N), —·—· Olbert (12°N) × 1·2, ○ Allkofer *et al* (1971), ● Bateman *et al* (1971), △ Bhattacharyya (1970), ▽ Nandi and Sinha (1970), ▲ Crookes and Rastin (1971), ■ present experiment (12°N), □ present data converted to a geomagnetic latitude of 45°N.

Olbert (1954) a correction of approximately +22 % is required near 1 GeV/c to convert the differential intensities for 12°N to latitudes greater than 45°N. Applying this correction, it is seen that our results closely resemble the best fit curve presented in the figure 2.

Crookes and Rastin (1971b) reported a measurement of absolute vertical integral intensities of muons at depths 31·6 and 36·3 hg cm^{-2} below sea level. The differential intensity obtained from these two underground measurements is $(1{\cdot}75 \pm 0{\cdot}52) \times 10^{-4}$ cm^{-2} sr^{-1} s^{-1} (GeV/c)$^{-1}$ for a mean muon momentum of 8 GeV/c at sea level. It is interesting to note that this result agrees with the present best fit curve. The recent muon spectrum measured by Nandi and Sinha (1970) using the Durgapur spectrograph at 12°N are also found to be in good agreement with the present best fit spectrum above about 9 GeV/c where the latitude effect is not so relevant. The Durgapur spectrum covers the momentum range 4–834 GeV/c and was normalized at 19·3 GeV/c to the value given by Hayman and Wolfendale. The spectrum of Hayman and Wolfendale (1962) however lies 25 %, 20 % and 12 % below the best fit curve in the momentum ranges 0·5–3, 3–7 and 7–10 GeV/c respectively. Even if the fact that the Durham spectrum normalized to the Rossi 1 GeV/c point is taken into account, this comparison shows that the Hayman and Wolfendale spectrum exhibits a different spectral character to that of the present best fit curve.

The present results at the lower latitude support the recent increase in the muon intensity observed at higher latitudes. This increase can be explained if both the effects of the multiple scattering loss and zig-zag motion of the particles in the lead absorber are properly considered. This conclusion is in agreement with that of Crookes and Rastin (1971).

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References

Allkofer O C, Andresen R D and Dau W D 1968 *Can. J. Phys.* **46** S301–5
Allkofer O C, Dau W D and Jokisch H 1970a *Phys. Lett.* **31B** 606–8
—— 1970b *Proc. 6th Interamerican Seminar on Cosmic Rays, La Paz* pp 937–48
Allkofer O C, Carstensen K and Dau W D 1971 *Phys. Lett.* **36B** 425–7
Ayre C A *et al* 1971 *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* (Hobart: University of Tasmania)
—— 1971 *J. Phys.* A: *Gen. Phys.* **4** L89–93
Bateman B J *et al* 1971 *Phys. Lett.* **36B** 144–8
Bhabha H J 1938 *Proc. R. Soc.* A **164** 257–94
Bhattacharyya D P 1970 *Z. Phys.* **234** 17–22
Crookes J N and Rastin B C 1971a *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* (Hobart: University of Tasmania)
—— 1971b *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* (Hobart: University of Tasmania)

De A K *et al* 1971 *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* (Hobart: University of Tasmania)
Eyges L 1948 *Phys. Rev.* **74** 1534–6
Fenyves E 1955 *Acta Phys. Hung.* **4** 363–74
Fukui S, Kitamura T and Murata Y 1957 *J. Phys. Soc. Japan* **12** 854–63
Greisen K 1942 *Phys. Rev.* **61** 212–21
Hayman P J and Wolfendale A W 1962 *Proc. Phys. Soc.* **80** 710–28
Kraushaar W L 1949 *Phys. Rev.* **76** 1045–58
Nandi B C and Sinha M S 1970 *Acta Phys. Hung.* **29** *Suppl.* 4 87–90
Olbert S 1954 *Phys. Rev.* **96** 1400–7
Pomerantz M A 1949 *Phys. Rev.* **75** 1721–8
Rossi B 1948 *Rev. mod. Phys.* **20** 537–83
Serre C 1967 *CERN Report* 67-5 pp 1–20
Sternheimer R M 1954 *Rev. sci. Instrum.* **25** 1070–5
Subramanian A *et al* 1958 *Nuovo Cim.* **7** 110–3
York C M 1952 *Phys. Rev.* **85** 998–1003