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Low momentum integral muon spectrum at sea level near the geomagnetic equator

Deba Prasad Bhattacharyya

Department of Physics, Presidency College, Calcutta, India

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Abstract. The vertical cosmic muon spectrum at sea level in the momentum range 0·32–3 GeV/c has been measured near the geomagnetic equator (at 12°N) by means of a flash-tube range spectrograph. The results have been compared with others obtained at similar and higher latitudes.

1. Introduction

The precise determination of the low momentum absolute sea level muon spectrum at various latitudes is necessary for the investigation of the influence of the earth's magnetic field on the muon spectrum and also for a knowledge of the composition of the primaries producing the muons.

Several investigations on the sea level cosmic muon spectra at low geomagnetic latitudes have been made by Kitamura and Minakawa (1953), Fukui *et al* (1955) and Basu and Sinha (1959). These authors have found muon intensity around 0·32 GeV/c and their results are in agreement with one another within the limits of statistical fluctuations. Later, Fukui *et al* (1957) have measured the muon intensities at 0·32 and 0·55 GeV/c respectively with better accuracy by their absorption spectrometer. Recently, Dau (1968) has measured the muon spectra at about 9 °N in the momentum range 0·2–30 GeV/c by his spark chamber magnetic spectrograph.

More recently De *et al* (1972a,b) have determined the low latitude (λ = 12 °N) muon intensities at 0·954, 1·05 and 1·20 GeV/c by means of an absorption spectrometer and they found an increase in muon intensity over those reported previously.

No direct absorption measurement of the absolute integral muon intensity above 1·2 GeV/c near the geomagnetic equator is available until now and a thorough analysis of the muon intensity problem is of interest all the more in view of the increase in muon intensity reported recently by Jokisch (1969) and De *et al* (1972a,b). The present paper reports the direct measurement of the absolute sea level muon spectrum in the range 0·32–3 GeV/c near the geomagnetic equator by means of a flash-tube range spectrograph in which the momentum of muons has been evaluated by the absorption measurements and the penetrating particles have been located by the neon flash-tube stacks. The experimental spectrum, after scattering and other corrections, has been compared with the low latitude spectra of Kitamura and Minakawa (1953), Fukui *et al* (1957), Dau (1968), Bateman *et al* (1971) and De *et al* (1972a,b) and the high latitude spectra of Greisen (1942), Dau (1968), Jokisch (1969) and Crookes and Rastin (1972).

The neon filled flash-tube stacks render a visual check on the validity of each event from the location of penetrating particle trajectories through the geometry defined by the GM telescope and identification of small showers within the detectors. The particles accompanying muons can be easily distinguished from the observed events. The amplitude ratio of the integral spectrum of accompanying particles to the integral spectrum of single muons has been estimated at different muon momenta and the results have been compared with that of Palmer (1964).

2. The experiment

The cosmic muon flux at sea level in the vertical direction at Calcutta (80 ft above sea level, 12 °N geomagnetic latitude and the corresponding vertical cut-off rigidity of primaries, $P_c = 13{\cdot}7$ GV) has been measured by an integral range spectrograph in the momentum range 0·32–3 GeV/*c*. The schematic diagram of the experimental arrangement is illustrated in figure 1. The experiment has been performed under lead absorbers Σ and T, the total thicknesses of which may be varied from 167 to 2082 g cm^{-2} of lead equivalent material within the detector. The muons of different momenta are allowed to traverse through the materials $\Sigma + \mathrm{T}$. Three neon flash-tube stacks, each containing 8 tubes per row and 9 tubes per column, have been used for the location of the penetrating particles. The flash tubes are of the type described by Coxell and Wolfendale (1960). These tubes contain commercial neon (98 % Ne, 2 % He and less than 150 volumes per

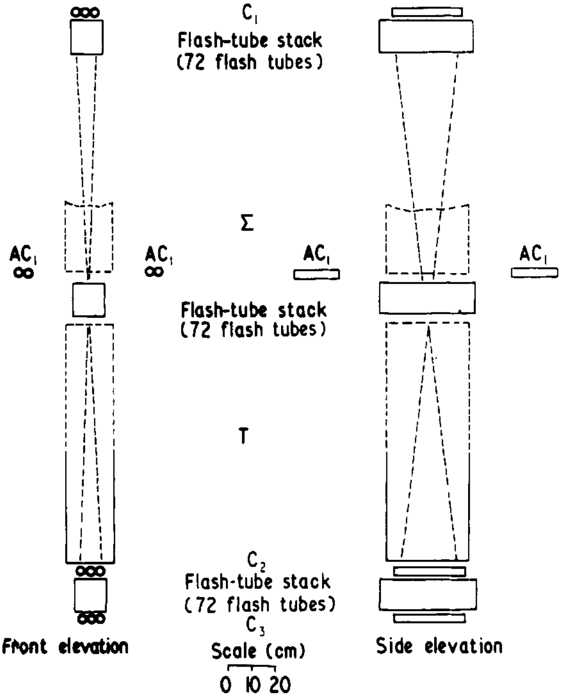

Figure 1. Schematic diagram of the experimental arrangement.

million A, O_2, N_2) to a pressure of 80 cm of mercury. The probability of a particle producing a flash in a single layer is $79 \pm 4\%$ for an applied electric intensity of 7·5 kV cm^{-1}. The passage of the particle through the apparatus has been identified by the coincidence with anticoincidence of Geiger trays $C_1C_2C_3$–AC_1.

The GM counters forming the telescope are filled with argon and ethyl alcohol vapour in the ratio 9:1 at a total pressure of 7 cm of mercury. The efficiency of GM counters at an operating potential 1 kV as determined by the method of Janossy and Kiss (1954) is 99 % for ionizing cosmic rays and the sensitive length of each counter is found to be 7 % less than the geometrical length of the counter cathode. The sensitive dimension of each of the beam defining counters is $30 \times 3{\cdot}5\ \mathrm{cm}^2$ determined by the method of Greisen and Neresen (1942) and the collection power (acceptance) of the experimental arrangement, defined by the GM trays C_1 and C_3, each with a sensitive area $3 \times 105\ \mathrm{cm}^2$, has been found to be 1·468 cm^2 sr.

The output pulse from the threefold coincidence with onefold anticoincidence circuits is made to trigger an EFP 60 pulser. Subsequent operation for the flashing of the flash tubes and the pulser circuit has been described in our previous report (Bhattacharyya 1970, 1971).

The ranges of muons corresponding to various absorber thicknesses have been converted into momenta by using the range–momentum relation presented by Serre (1967). The effective ranges are also corrected for the zigzag motion of the particles due to Coulomb scattering, by using the method of Koenig (1946). This value ranges from 2 to 1 % in the muon momentum interval 0·32–3 GeV/*c*. The straggling correction is appreciably smaller and is neglected.

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

The effective time has been calculated from the operating time by subtracting the dead time introduced by the cycling operation and quenching pulse applied to GM counters.

3. Results and discussion

The experiment has been continued for 364 hours and the observed events have been divided into three categories: (i) those showing single incident particles, (ii) those showing incident penetrating particles accompanied by some other particles, and (iii) those which cannot show a single unambiguous particle, caused by accidental coincidence and showers causing the majority of tubes to glow. These events which are 3 % of the total number of events have been rejected.

Figure 2 shows the ratio of integral intensity of accompanying particles to the integral intensity of single particles as a function of muon momentum. It appears from the figure that there is an increase of the accompanying particle to single particle ratio with increasing muon momentum and this is in agreement with the experimental results of Palmer (1964), but the percentage of the accompaniment is appreciably smaller in the present experiment. This may arise due to the insertion of the anticoincidence trays which reduce the frequency of large air showers.

Some particles which have passed through C_1 and are travelling in such a direction that they should hit counters C_2 and C_3, might be scattered away from C_2 and C_3. This effect is largely compensated by the particles which are scattered in such a direction that they actually hit counter C_3. The net loss of particles in Σ and T due to

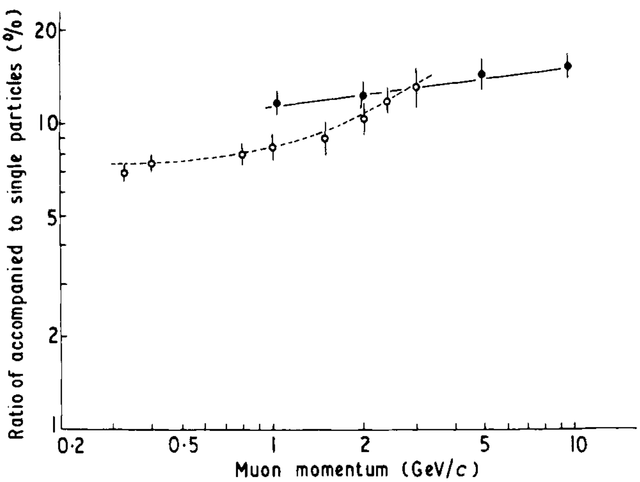

Figure 2. The ratio of the integral intensity of accompanied particles to the integral intensity of single particles as a function of muon momentum. ● Palmer (1964); ○ present work.

multiple scattering has been estimated by using Germain's (1949) method. The estimated number of muons scattered out of the acceptance of the range spectrograph varies from 0·4–1·7 % of the observed integral counts for muon momentum range 1–3 GeV/*c*.

The corrected absolute integral spectrum of single muons has been plotted in figure 3 along with the spectra of different workers. The absolute muon intensity obtained from our track visualizer data at about 1 GeV/*c* is of the order of 11 % less than the value of De *et al* (1972a,b) estimated from their absorption spectrometer experiment. This difference may be attributed to the failure of the estimation of the actual accompanying events counted by their range spectrometer. Their result almost follows the high latitude (55 °N) experimental Kiel muon spectrum of Dau (1968). The theoretical high latitude spectrum (full curve in figure 3) at sea level, calculated by Allkofer *et al* (1971, to be referred to as ACD) according to the formula of Barrett *et al* (1952), is in agreement with the range spectrometer results of Jokisch (1969) but lies above the magnetic spectrometer data of Dau (1968) for 55 °N. Following the procedure of ACD and taking the value of $A = 0{\cdot}169$ in Barrett *et al*'s formula and keeping other parameters the same as those used by ACD, the theoretical low latitude absolute sea level integral muon spectrum has been plotted in the same figure which agrees with the present work and Dau (1968) (9 °N) above muon momentum 0·7 GeV/*c*.

Our integral low latitude muon intensity at 0·32 GeV/*c* is lower than the high latitude corrected intensity of Crookes and Rastin (1972) by 25 % and of Greisen (1942) by 14 %. Though Crookes and Rastin find an increase in the Greisen intensity of 9 % but not of 26 % as has been found by Allkofer *et al* (1970). The low latitude data of Fukui *et al* (1957) agree well with our spectrum at muon momenta 0·32 and 0·55 GeV/*c* respectively. It appears from the present review that the calculated spectrum of ACD at 55 °N is higher than the present work by 30–15 % in the muon momentum range 0·32–1·8 GeV/*c* and by about 10 % in the region around 3 GeV/*c*. The high latitude spectrum of Dau (55 °N) shows a maximum difference of 20 % with our muon intensity at 0·6 GeV/*c* but agrees around 2·6 GeV/*c*. In any case the difference in these spectra may arise due to systematic errors in assessing the multiple factors involved in evaluating

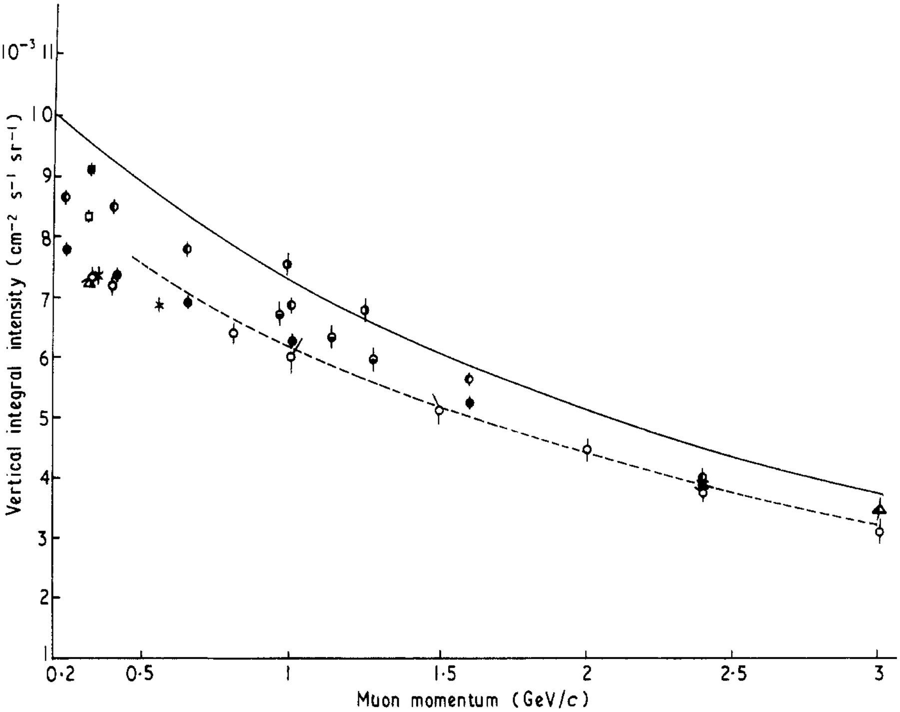

Figure 3. The absolute sea level integral muon spectrum of the present work together with the results of other workers at different locations. Low latitude data: ● Dau (1968), $\lambda = 9$ °N; ◒ De *et al* (1972a,b), $\lambda = 12$ °N; ○ present work, $\lambda = 12$ °N; ▲ Kitamura and Minakawa (1953), $\lambda = 24$ °N; × Fukui *et al* (1957), $\lambda = 24$ °N; △ Bateman *et al* (1971), $\lambda \simeq 25$ °N; --- theoretical spectrum, $\lambda \leqslant 24$ °N. High latitude data: ☐ Greisen (1942), $\lambda \simeq 50$ °N; ■ Crookes and Rastin (1972), $\lambda = 53$ °N; ◐ Dau (1968), $\lambda = 55$ °N; ◑ Jokisch (1969), $\lambda = 55$ °N; —— theoretical spectrum, $\lambda \simeq 55$ °N.

absolute intensity at the same location. The above review indicates a variation of muon intensity below 2 GeV/*c* due to the change of geomagnetic latitude apart from the systematic instrumental errors, and this variation may arise out of many factors: the effect caused by the normal variation of the atmospheric temperature with latitude, the influence of the atmospheric density on meson decay and solar activity. All of these effects, however, diminish slowly with increasing momentum of the particle.

The variation of our muon intensity (figure 3) with respect to the Kiel spectra cannot arise from the eleven year cycle since the experiments of the Kiel group (Dau 1968, Jokisch 1969) and ours were performed around the year 1969 when the solar activity was a maximum. The relative change of the differential sea level muon spectrum in the range 0·3–3 GeV/*c* due to solar activity calculated by Allkofer and Dau (1969) using Jabs' (1967) theory is about 8 % near the geomagnetic equator and this value comes out to be about 15 % near poles. The present spectrum shows an overall lower intensity, when compared to recent high latitude spectra of other workers, due to the maximum solar activity besides the geomagnetic effects. The meteorological conditions can influence only a small variation in muon intensity of about 3 % below 1 GeV/*c*. The calculated variation of the differential muon spectra after Olbert (1953) can explain only 8–2 % in the range 0·32–3 GeV/*c*. So the major variation in muon intensity in figure 3 appears to be due to (i) the exclusion of low energy primary nuclei by the earth's magnetic field at low latitudes, (ii) estimation of the bias of rejection of accompanied events of muons and (iii) instrumental errors.

4. Conclusion

The present absolute integral muon spectrum gives information about the spectral shape of the sea level muons near the equatorial region in the momentum range 0·32–3 GeV/*c*. The flash-tube range spectrograph yielding the present muon spectrum is the first to be in operation near the geomagnetic equator. Our sea level muon intensity at the standard normalizing point 1 GeV/*c* is 15 % lower than that found by Dau (1968) at 55 °N. The present results are more or less in agreement with the low latitude muon spectra of Kitamura and Minakawa (1953) at 24 °N, Fukui *et al* (1957) at 24 °N and Dau at 9 °N but show an 11 % decrease when compared to those of De *et al* (1972a,b) at 12 °N at around 1 GeV/*c*.

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