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Absolute Vertical Intensity of Muons near Sea Level*

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Current interest in an absolute measurement of the vertical intensity of muons stimulated the present research. A novel method for the classification of events, and in particular the separation of muons from the soft component, has enabled the determination of a set of relatively precise and reliable measurements. The results so obtained are somewhat lower than the few other recently reported measurements.

I. INTRODUCTION

In a review article in 1948 Rossi[1] gave values for the differential and integral vertical intensities of muons (the "hard component") near 1 GeV/c, which for many years stood as the accepted normalization points for other measurements in the vertical direction. Little attention had been paid to verifying Rossi's values until relatively recently, since the interpretation of muon spectrometric data relies very much more on the shape of the spectrum than on absolute values. Lately, however, Allkofer *et al.*[2] have indicated that Rossi's figures may be as much as 25% too low, and new interest in accurately determining such intensities has been generated. The present experiment was designed to measure integral intensities with cutoffs in the low-momentum region below 1 GeV/c. The measurements were made at Winnipeg, Canada (geomagnetic latitude 49.9°N, elevation 236 m).

Measurement of the muon intensity with a given apparatus requires a knowledge of

(1) the loss of particles due to inefficiency of the detectors employed in the apparatus,
(2) the probable error in the determination of the geometrical aperture of the apparatus,
(3) the effect on the intensity measurement due to electromagnetic scattering of the muons in the apparatus, and
(4) the extent to which the data are contaminated by events in which a muon did not traverse the whole apparatus (such events may be produced by extensive air showers).

The present experiment employs a scintillation-counter telescope for which effects (1) and (2) are reduced to negligible levels, while the method of analysis is such that the magnitudes of effects (3) and (4) are estimated to be no more than 2%. This is accomplished without the aid of track location techniques.

II. EXPERIMENTAL

The apparatus, depicted in Fig. 1, consisted essentially of two parts: a set of five scintillation

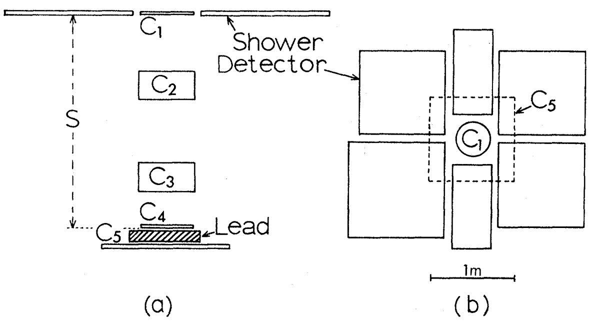

FIG. 1. (a) Side view of the apparatus. Vertical detector separation is drawn to a reduced scale. C_1, C_2, C_3, C_4 are circular in cross section. S was either 512 or 528 cm. (b) Top view of the apparatus showing the arrangement of the shower detectors.

detectors, C_1 through C_5, which formed a simple vertical-particle telescope, and a companion shower-detection array of six large area scintillators arranged in a horizontal plane surrounding the uppermost detector of the telescope (C_1). Detectors C_1 and C_4 were thin discs of plastic scintillator (diameter: 36.5 cm; thickness: 1.25 cm) separated by ~5.2 m, and defined the aperture of the telescope. C_2 and C_3 were cylindrical in shape and of slightly larger diameter than C_1 and C_4 (diameter: 38.1 cm; thickness: 20.3 cm).

Lead absorber was placed between detector C_4 and the large-area detector C_5 (85 cm$\times$85 cm); this position of the lead minimized any reduction of the counting rate due to multiple scattering of the incident particles by the absorber.

A basic slow fourfold coincidence ($\tau = 1$ μs) of detectors $C_1C_2C_3C_4$ constituted an event, and triggered an automatic readout of additional data on punched paper tape, including:

(1) the time of day in minutes,

(2) digitized pulse-height data from detectors C_1, C_2, C_3, and C_4,

(3) the status of detector C_5 during the event, and

(4) the status of each member detector of the shower array.

Runs were made with two different thicknesses t of lead absorber; these were $t = 114$ and 285 g cm^{-2}. The presence of the extra lead in the latter run necessitated a change in the separation of the detector pair C_1C_4 from 528 to 512 cm. The corresponding geometrical factor of the telescope changed from 3.93 to 4.18 cm^{2}sr. The maximum zenith angle for single-particle traversal of the apparatus was 4°.

The momentum cutoffs associated with the telescope in these configurations were determined using muon-range tables provided by Barkas and Berger.[3] In order to have produced a trigger, a muon need only have penetrated the material of the telescope lying above detector C_4, some 98 g cm^{-2}, corresponding to a momentum threshold of 0.31 GeV/c. The minimum momentum of muons which also penetrated the lead absorber and triggered detector C_5 was calculated to be 0.44 GeV/c for the case $t = 114$ g cm^{-2}, and 0.66 GeV/c for $t = 285$ g cm^{-2}.

III. TREATMENT OF DATA

The chief problem of the data analysis was to eliminate events in which no penetrating particle(s) had passed through the aperture of the telescope. Such events were caused by extensive air showers which had directions of approach lying outside the telescope solid angle and which were dense enough to produce a fourfold coincidence. Rejection of shower events was accomplished using pulse-height analysis and the information provided by the shower detection array.

An initial categorization of the data was carried out according to the disposition of the shower array in each event. Three categories were used:

(1) "U" (unaccompanied) events, during which the shower array had not been triggered,

(2) "A" (accompanied) events, during which only one shower detector had been triggered, and

(3) "E" (extensive) events, during which more than one shower detector had been triggered.

The intensities of the events in these classes, obtained by dividing the counting rate by the telescope geometrical factor, are listed in Table I. The numbers in the first two rows correspond to the lower momentum cutoff of 0.31 GeV/c, while the rest refer only to events in which detector C_5 had been triggered, indicating, at least for non-shower events, that the particles had penetrated the lead absorber.

It was evident that the E category was to be associated with dense air-shower events, for in 60% of these cases all six shower-array detectors had been triggered simultaneously. The reason for distinguishing "A" from "E" events will be made clearer in the following discussion of the pulse-height spectra.

Figure 2(a) shows the pulse-height spectra from detector C_2 for the three categories of event (U, A, E). The U and A classes exhibited the well-defined Landau peaks characteristic of muon ionization, while the E class possessed a broad pulse-height spectrum. (The features in the spectra above channel 30 are due to limiting in the phototube preamplifiers and in the analog-to-digital converters used to encode the pulse heights.) It was clear from the spectral shape that the muon content of the A category was apprecia-

TABLE I. Classification of the data.

		Integral intensity (10^{-3} cm^{-2} sr^{-1} s^{-1}) U	A	E
(C_1–C_4) coincidences; $p_0 = 0.31$ GeV/c	No rejection (total rates)	8.62	0.43	4.53
	Rejecting low-pulse events	7.88 $I_U(>p_0)$	0.25	1.12
(C_1–C_4), C_5 coincidences; $t = 114$ g cm^{-2}; $p_0 = 0.44$ GeV/c	No rejection	8.12	0.35	4.21
	Rejecting low-pulse events	7.52 $I_U(>p_0)$	0.24	1.08
	Absorption exp.	6.32	0.15	0.14
(C_1–C_4), C_5 coincidences; $t = 285$ g cm^{-2}; $p_0 = 0.66$ GeV/c	No rejection	7.50	0.34	4.35
	Rejecting low-pulse events	6.98 $I_U(>p_0)$	0.22	1.14
	Absorption exp.	5.70	0.14	0.10

ble. This type of event most probably originated when a shower detector was triggered by a secondary knock-on electron, occasionally produced by a muon as it passed through the laboratory roof (containing 7 g cm^{-2}) above the apparatus.

The discriminator thresholds employed in the experiment were set very low to avoid fluctuations in muon detection efficiency caused by drift in the electronics. As a result, many events (32% of the recorded events) occurred in which one or more of the pulse heights from detectors $C_1 C_2 C_3 C_4$ lay below the lower edge of the Landau

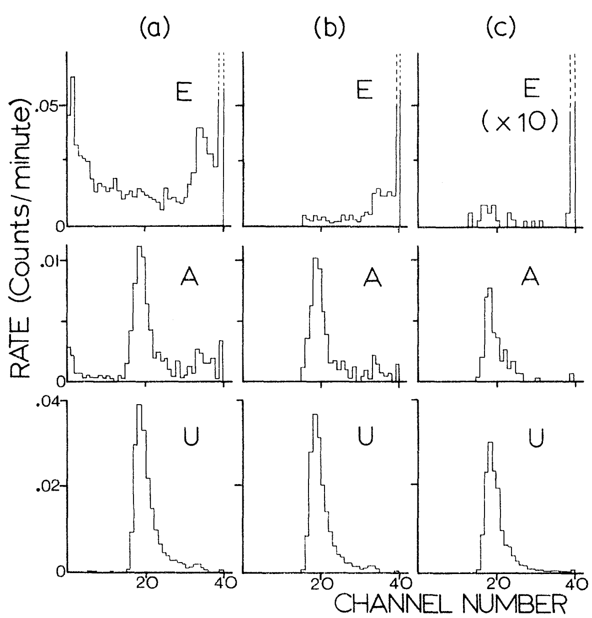

FIG. 2. Pulse-height spectra in detector C_2 for the event categories U, A, E : (a) no rejection of events; (b) rejecting events with low pulse heights; (c) absorption-experiment results.

peak, i.e., channel 15 in C_2. The term "low pulses" will be used to refer to amplitudes in this pulse-height range. The most likely sources of such events were extensive air showers in which the detectors had not all been triggered by the same particle. Path lengths (and ionization losses) in individual detectors for events of this kind could thus be very small. On the other hand for events in which a penetrating particle had passed through all four detectors within the aperture, the number of low pulses which could arise by corner clipping (possible only in C_1 and C_4) or by inefficiencies in light collection, was expected to be very small. In fact, $\simeq 1.5\%$ of the U events contained low pulses in C_2. An initial data rejection was therefore performed by eliminating all events having one or more low pulses, and a correction subsequently applied to account for the loss of true muons in this process.

The effects of "low pulse" event rejection are indicated in Table I and Fig. 2(b). The effect is most noticeable for the E events of which some 75% were rejected, compared with 8% of the U events.

The pulse-height spectra of the surviving E events [Fig. 2(b)] still did not exhibit single particle peaks, most of the pulse heights being considerably higher. However, since the E events still constituted 14% of the total data sample, a separate "absorption experiment" was carried out in an attempt to determine their origin.

The geometry of the telescope was altered so that the extreme detectors C_1 and C_4 were shielded from above by at least 10 cm of lead absorber. For these runs the full former thickness of absorber (t) was placed immediately above the scintillator of detector C_4, while an additional 10 cm of lead was inserted in the telescope aperture above C_1. This new configuration imposed the restriction that in order for a fourfold coincidence to occur, a penetrating particle must have passed through each of C_1 and C_4.

The resulting intensities (after rejection of low-pulse events) are given in Table I, labeled absorption experiment. The intensity of U events fell by 16% for $t = 114$ g cm^{-2} and 18% for $t = 285$ g cm^{-2}, of which 4% was attributed to the higher momentum cutoff due to the extra 10 cm of lead in the telescope, and the remainder to scattering of particles out of the aperture by the lead. The striking feature of the results is that the rates of E events were reduced by 87% and 91%, respectively.

The spectrum of "penetrating" E events [Fig. 2(c)] still contained a number of limiting pulse heights, although relatively fewer of these occurred in the spectra from the shielded detectors C_1 and C_4 (not shown). It was concluded that most of the E events were certainly the result of extensive air showers triggering the telescope and that the small number surviving in the absorption experiment (now <2% of the total intensity) were due to one or more penetrating particles accompanied by a shower.

The muon intensity $I_\mu(>p_0)$ for a given momentum cutoff p_0 was therefore calculated from the rate of no low-pulse events, $I_U(>p_0)$ (see Table II), corrected for muons lost in the initial pulse-height rejection (l = fraction rejected) and for the fraction of muons contained in the A and E categories (a). Thus:

$$I_\mu(>p_0) = I_U(>p_0)(1 + l + a) .$$

The number of U events having a low pulse in only one of the four detectors was $\simeq$7%. These events were apparently muon-produced, since the distribution of pulse heights in the remaining three detectors was consistent with random selection from the Landau peaks. Thus, a value for l was calculated from the number of these "one low pulse" events in the U sample. Values for l at the various momentum thresholds are given in Table II.

An average value of $a = 0.045$ was calculated, using the data from the absorption experiment. This value was used for all three momentum cutoffs.

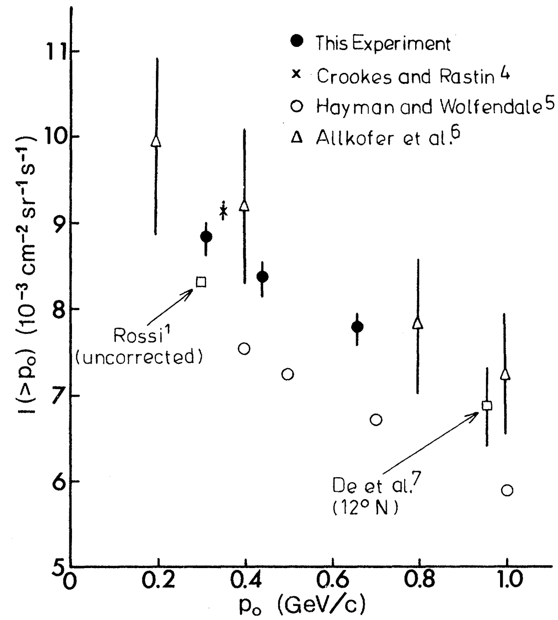

FIG. 3. Comparison of present results with some previous measurements. [Note that the point of De *et al.* (Ref. 7) should be corrected for latitude dependence before direct comparison with the other results.]

IV. RESULTS

The calculated integral intensities are given in Table II and are plotted in Fig. 3. (See Refs. 4–7.) Although the statistical uncertainty in the present results is $\simeq$1%, the indicated errors have been enlarged to indicate the potential presence of additional systematic errors. The first of these is a possible 2% overestimate of the muon intensity by the inclusion of the E counting rate in the intensity calculation, for the muon content of the E class is essentially unknown. The second source of systematic error is the scattering of muons by the matter of the telescope. As pointed out earlier, the position of the lead absorber was chosen to minimize the effect of scattering due to its presence. Any significant net loss of particles so caused would show up as an enhancement of the intensity at 0.31 GeV/c (no lead absorber) relative to the trend indicated by the other points. The near linear dependence of I_μ on momentum cutoff

TABLE II. Correction factors and results.

p_0	l	a	$I_U(>p_0)$ (10^{-3} cm^{-2} sr^{-1} s^{-1})	$I_\mu(>p_0)$ (10^{-3} cm^{-2} sr^{-1} s^{-1})
0.31	0.078	0.045	7.88	$8.84^{+0.15}_{-0.24}$
0.44	0.067	0.045	7.52	$8.36^{+0.17}_{-0.25}$
0.66	0.070	0.045	6.98	$7.78^{+0.16}_{-0.23}$

p_0 indicated that such an effect, if any, was small. However, the remainder of the telescope contained some 98 g cm^{-2} of matter, and thus intensity values may have been somewhat underestimated due to net scattering of muons out of the aperture by the detectors and their housings. It was estimated that in terms of scattering effect, this amount of low-Z material was equivalent to $\simeq$1 cm of lead absorber. An additional experimental run with 1 cm of lead placed above detector C_2 established an upper limit of 1% on any reduction of the integral intensity caused by scattering of muons out of the telescope aperture.

Thus, the uncertainties indicated in Fig. 3 include a positive 1% contribution from scattering and a negative 2% from the E events.

V. COMPARISON WITH OTHER DATA AND CONCLUSIONS

The present results indicate a somewhat higher (~7%) intensity than the Rossi[1] value mentioned in Sec. I [$I(>0.3\ \text{GeV}/c) = 8.3\times10^{-3}\ \text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$]. However, a correction, applied to Rossi's result by Crookes and Rastin,[4] for muons scattered out of the aperture by the lead absorber (no details of the correction procedure were supplied) indicated that the true intensity may have been underestimated by 18.3%, and that the corrected cutoff momentum should be 0.33 GeV/c, placing the Rossi value considerably higher than our measurements. Crookes and Rastin's own measurement, $I(>0.35\ \text{GeV}/c) = (9.13\pm0.12)\times10^{-3}\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$, also is some 5% higher than the present results, as indicated in Fig. 3.

From measurements made on the early Durham spectrograph, Hayman and Wolfendale[5] presented a "best fit" integral spectrum, also shown in Fig. 3, lying some 12% below the present spectrum, while Allkofer *et al.*[6] in a review of some of their own experiments calculated a "best fit" spectrum, which in the region of interest was 8% higher than the present spectrum, though with a relatively large error band (±10%). In both cases, however, the integral spectrum was the result of combined data from a number of separate experiments, and therefore was subject to both normalization and statistical errors. No estimate of uncertainty was given for the Durham spectrum.

All the above measurements were made at high latitude λ in a range where little variation of I_μ with λ is expected. A recent measurement at low λ (12°N) has been made by De *et al.*[7] who obtained $I(>0.954\ \text{GeV}/c) = (6.86\pm0.03)\times10^{-3}\ \text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$. This also is shown in Fig. 3, though a correction for the latitude dependence of I should be made before comparing with the other measurements. De *et al.* estimated this correction to amount to 8.3%, which brings their point into line with Allkofer's spectrum.

Thus, it appears that the present intensity measurements may lie somewhat lower than other currently reported results, though there is agreement within the quoted experimental errors. Measurements of a decade ago, and older, clearly lie below the newer data. An advantage of the present experiment over others in which estimates of the integral intensity have been made, is that no normalization procedure has been used at any stage of the process, thereby eliminating a rather common, and often underestimated, source of uncertainty from the results. It is noted that all of the recent measurements have been made within about two years of the latest sunspot maximum which occurred in 1969/70, and thus intensity differences of no more than 1–2% between the various results would be expected from this source.

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