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The Mesotron Momentum Spectrum at 4.35-km Altitude

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The mesotron momentum spectrum has been determined at Mount Evans, Colorado, from the shape of the absorption curve in lead as measured by Geiger-Müller counter telescopes. Special attention was paid to eliminating the contribution of single electrons to the measured intensity. A large number of low energy mesotrons were found, resulting in a sharp maximum of the momentum spectrum lying between 1 and 2×10^8 ev/c. A simple power law is not adequate to describe the spectrum in the entire region investigated.

INTRODUCTION

THE mesotron spectrum at intermediate altitudes has usually been approximated in calculations by assuming a distribution in energy similar to that found at sea level.[1–4] The function generally used has been in the form of a power law with an exponent of about 3, extending from about 10^9 ev to very high energies. In the present investigation, the distribution was determined by absorption measurements in lead, with thicknesses extending from 0.5 cm to 91.5 cm of lead. Because the mesotrons lose energy in solid material by ionization processes only, and therefore have a definite range depending only on the thickness of material traversed and the energy of the particle, a lower energy limit can be assigned to those mesotrons which are able to penetrate any given thickness of material. The expressions for energy loss as a function of material traversed, such as the Bethe-Bloch formula, have been well tested and found to be reliable at least in the region of 2 to 7×10^8 ev.[5] The formulae given by B. Rossi and K. Greisen[6] were found convenient to use here. Since the absorption curve of mesotrons represents an integral spectrum of these particles, the usual form of differential energy spectrum can be directly obtained from the experimental points. For convenience in comparison with cloud-chamber measurements, the results to be given are expressed as momenta, in units of ev/c, bearing the usual relation to energy of $E=(p^2+\mu^2)^{\frac{1}{2}}-\mu^2$, where the mass of the mesotron has been taken as 10^8 ev/c^2, corresponding to 200 electron masses.[7]

EXPERIMENTAL PROCEDURE

The experiments were carried out at the Mount Evans Laboratory, Colorado (4.35-km altitude, 45.7-cm Hg pressure). Two independent Geiger-Müller counter-tube telescopes shown in Fig. 1 were used. The individual counting rates were adjusted for best agreement at two points. In the arrangement of Fig. 1a, counter tubes were connected in pairs and arranged to give fourfold coincidence between counter pairs 1, 2, 3, and 4, measured with a recording set having a resolving power of about 10^{-4} second. Each set

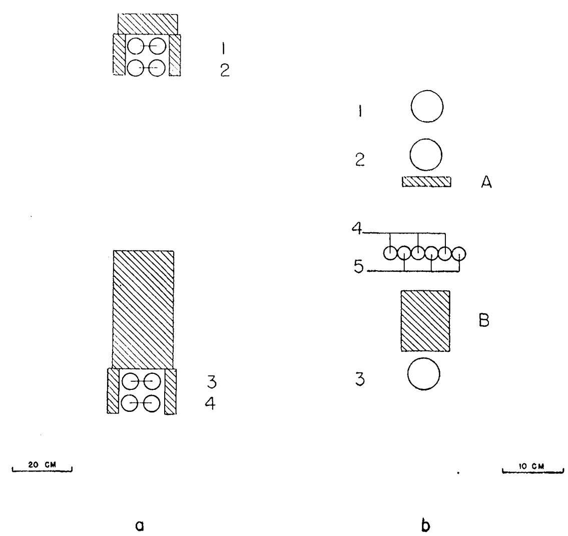

FIG. 1. Arrangement of counters and absorbers.

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of four tubes was housed in 5 cm of lead to reduce the effects of soft side showers. In order to correct for penetrating side showers, the two boxes were placed at the same height so that one particle could not cause a coincidence. This correction, which was of the order of 4 percent, was subtracted from the measured intensity for each thickness of absorber used. No scattering correction was made since, with the counter arrangement used, the chance for scattering into coincidence is almost the same as for scattering out of coincidence. Absorber thicknesses ranging from 15 cm to 91.5 cm of lead were used in this arrangement. The lower limit of 15 cm of lead was sufficient to assure that only mesotrons were being detected.

The arrangement shown in Fig. 1b was used with absorber thicknesses from 0 to 20 cm of lead. Coincidences of counters 1, 2, 3 which defined the solid angle subtended by the vertical telescope were recorded with a circuit of higher resolving power ($\tau = 10^{-5}$ sec.). Corrections for side showers were determined by measuring out of line coincidences with the top counter displaced. With less than 10 cm of lead in the telescope it became necessary to distinguish between mesotrons and electrons. This was done by placing a 1.5-cm lead block in position A and recording the resultant showers of two or more particles emerging from the lead, coincident with a discharge of counters 1, 2, 3. These fivefold discharges of the combined shower and vertical set could be caused by (a) knock-on electrons from the lead block A accompanying mesotrons, (b) electrons generating a cascade shower in lead A, (c) air showers.

Only those events of type (b) were subtracted from the measured vertical intensity (coincidence 1, 2, 3). Events (c) have no relation to the absorber B and only provide a constant background counting rate for the shower set (4, 5). These events (c) were determined by measuring the counting rate with the lead A removed. Type (a) was separated from (b) in order that the correction contains effects owing only to incident electrons. This separation was accomplished by assuming that 10 cm of lead in position B would be sufficient to stop all electrons which entered the apparatus as single particles. Those electrons of high enough energy to penetrate 11.5 cm would have high probability of being accompanied by additional particles when entering the apparatus, and hence would be eliminated by the displaced counter measurements. After the background was eliminated, the frequency of fivefold coincidences with 10 cm of lead in position B was taken to be owing to knock-on electrons accompanying mesotrons. To a first-order approximation at least, this type of event is a constant percentage of the incident mesotrons. The increase, then, in the rate of shower-producing rays with decreasing thickness of absorber in position B was attributed to the electron component of the total cosmic-ray intensity. Corrections were made for the change in efficiency of the shower tray for different energies of incident electrons.

CALCULATIONS

The efficiency of the shower-detecting tray as a function of the number of particles emerging from the lead A can be calculated from the geometrical arrangement of the counter tubes. The number of particles to be expected from electrons of various energies was estimated from Rossi and Greisen's discussion of the cascade process.[6] In calculating the efficiency of the shower tray, it was assumed that in order for the bottom counter 3 to be discharged, at least one particle must have gone through the area covered by the tray and discharged one of the counters belonging to either 4 or 5. The problem then becomes the determination of the compound probability that (a) if N particles emerge from the lead block A, what is the chance that they will emerge in such a direction as to fall within the area of the tray, and (b) what is the chance that the tray will respond to these particles since only half of the area is available for registering a coincidence. Let P_n be defined as the probability that if N particles emerge from the lead *exactly* n of them will strike the tray; let p_n be the probability that if n particles fall in the sensitive area, the tray will register a coincidence. The probability of detecting an N-fold shower may then be written as

$$\Pi_N = \sum_{n=1}^{N-1} P_n p_n.$$

The value of P_n was estimated from the data on cascade showers reported by Froman and Stearns.[8] For the experimental arrangement of Fig. 1b, at least 80 percent of the shower particles should emerge from the lead in such a direction that they will fall within the active area of the tray. This value was assumed to be independent of the total amount of absorber in the telescope. The error introduced by this assumption will tend to discriminate against the showers produced by high energy electrons where the efficiency of detection is already high and the frequency is expected to be low. The value of p_n was taken as 0.5 since the six tubes comprising the tray were connected so that alternate ones were in parallel. Any inefficiency of the counter tubes themselves which was of the order of 1 percent could be neglected as a second-order effect.

The initial energy of an electron required to penetrate a given thickness of absorber and emerge with one descendant was estimated from calculations of the cascade theory as developed by Arley[9] and also by Rossi and Greisen.[10] From the same calculations, the number of particles to be expected after passing through 1.5 cm of lead was determined for each incident energy. The change in shower-producing rays observed with changing thickness of absorber could then be ascribed to certain energy ranges of incident electrons and an estimate made of the probable size of showers accompanying these rays. This permitted assigning an average efficiency of detection to each range of absorbing thickness. Table I lists the result of these calculations; their application to the data is given in Table II.

EXPERIMENTAL RESULTS

The experimental results are listed in Table III and shown graphically in Fig. 2. The values of $N(e)$ cannot be interpreted accurately as an energy spectrum of the electron component, since (a) air showers, and consequently high energy electrons, have been eliminated, and (b) the penetration of cosmic-ray electrons is not an exact measure of their energy. The value given for the electron intensity at 0.5 cm is an extrapolated figure. The mesotron intensity at 0 cm was taken so that the number of very slow mesotrons, which are heavily ionizing, was limited to less than one percent of the total intensity, in agreement with cloud-chamber studies at this altitude.[11] The resulting spectrum, however, is not sensitive to either of these extrapolations.

TABLE I. Results of calculation of efficiency of detection of electrons.

Total absorber cm of Pb	Min. energy of incident electron	No. of assoc. particles of $E>10$ Mev below 1.5 cm of Pb	Efficiency assigned
1.5	0.5×10^8 ev	1	0.40
3.5	2.0×10^8 ev	4	0.90
5.5	5.5×10^8 ev	10	1.00
11.5	$20.\ \times10^8$ ev	100	

TABLE II. The electron intensity corrected for efficiency of detection. The measured intensity was adjusted by subtracting the contribution owing to air showers (0.24 c.p.m.) and knock-on electrons. This latter component was estimated to be one percent of the vertical penetrating particles from measurements with 11.5 cm of lead.

Total absorber cm of Pb	Vertical intensity c.p.m.	5-fold shower and vertical combination c.p.m.	Electron intensity c.p.m.	Electron intensity (corrected) c.p.m.
1.5	7.00	0.98	0.67	1.06
3.5	6.10	0.73	0.43	0.46
5.5	5.43	0.43	0.14	0.14
7.5	5.02	0.32	0.03	0.03
11.5	4.57	0.28	0.00	0.00

TABLE III. Compilation of data. $N_{(t)}$ is the measured vertical intensity together with the standard deviation of the measurements; $N_{(e)}$ is the electron correction taken from Table II. $N_{(m)}$ is the resultant vertical mesotron component; $I_{(m)}$ gives the mesotron intensity in percentages of the total.

Cm of Pb	Minimum momentum $\times10^8$ ev/c	$N(t)$ c.p.m.	Std. dev.	$N(e)$	$N(m)$ corrected	$I(n)$ %
0	0	9.50	.09		6.25	100
0.5	0.65	8.20	.09	2.00	6.20	99.4
1.5	0.95	7.00	.08	1.06*	5.94	95.0
3.5	1.35	6.10	.11	.46	5.64	90.2
5.5	1.70	5.43	.07	.14	5.29	84.6
7.5	2.00	5.02	.08	.03	4.99	79.9
11.5	2.50	4.57	.08	.00	4.57	73.0
15.2	3.00	4.33	.04		4.33	69.2
20.3	3.70	4.15	.07		4.15	66.5
30.5	5.00	3.49	.07		3.49	55.8
50.8	7.80	2.83	.07		2.83	45.3
91.5	13.75	2.08	.05		2.08	33.3

* Note that the electron component at 1.5-cm lead corresponds to about 18 percent of the total mesotron intensity. Considering a minimum energy of 1×10^8 ev for these electrons, this is consistent with results recently reported by W. E. Hazen, Phys. Rev. **65**, 67 (1944).

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[10] B. Rossi and K. Greisen, reference 6, p. 309.
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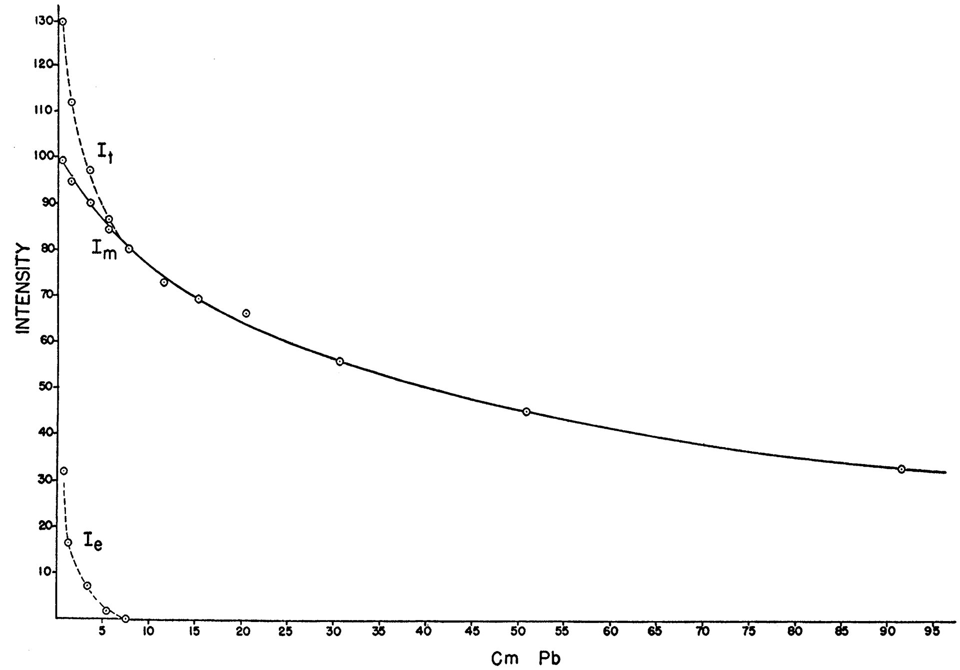

FIG. 2. Absorption of cosmic radiation at Mount Evans, Colorado (el. 4.35 km). It represents the total measured intensity I_e, the shower-producing component after correcting for efficiency. The difference curve I_m gives the mesotron absorption adjusted to be 100 at 0 cm.

Figure 3 is obtained from the smooth curve of Fig. 2. The units are percent of total intensity per hundred million electron volts. The shape of the entire spectrum cannot be represented by a simple mathematical function. Between 2×10^8 ev/c and 10^9 ev/c, however, a rough fit can be obtained for the momentum spectrum of mesotrons by $dN/dP = Ap^{-1.4}$, where A represents an arbitrary constant. In view of the very different spectrum observed at sea level, there is no justification in extending this analytical expression to predict the shape of the curve beyond the region covered by the experimental data.

The presence of the prominent maximum in

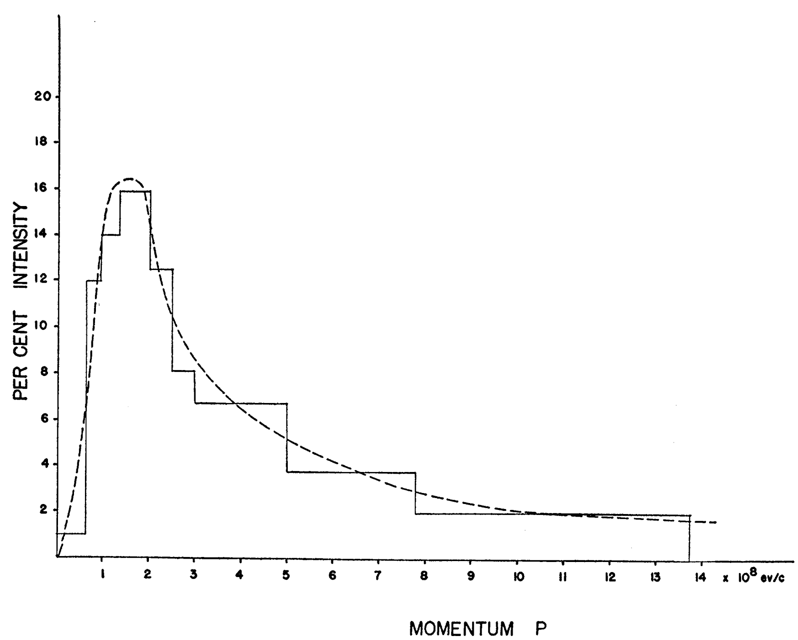

FIG. 3. Differential momentum spectrum at Mount Evans (4.35 km). Abscissa is momenta values obtained by range-momenta relationships. Ordinate is the percent of total intensity per interval of 10^8 ev/c.

the region between 1 and 2×10^8 ev/c cannot easily be accounted for on the usual basis of a mesotron production layer at 16 km and subsequent spontaneous decay in the atmosphere. The shift of the maximum to lower energies and the large number of mesotrons between 10^8 and 10^9 ev/c would require special assumptions in regard to the distribution with which they are created. It is highly probable, therefore, that many of these mesotrons are created relatively close to the point of observation (Mount Evans). Since the number of protons observed near this altitude[11] does not seem large enough to be the principal agent of production, neutral radiation, such as photons or other neutral particles, may be responsible for most of these low energy mesotrons. Although these production processes at low altitudes have been discussed before,[12,13] the importance of their contribution in the description of the spectrum has not been emphasized.

If the observed momentum distribution of Fig. 3 is used to calculate a mesotron spectrum for the elevation of Echo Lake, Colorado (3.24 km), using the usual formulae for decay and ionization loss, one obtains a curve shown in Fig. 4 that is in reasonably good agreement with the data obtained by anticoincidence measurements of Rossi, Greisen, Stearns, Froman, and Koontz[14] taken at this station. This would indicate that the mesotron production processes do not contribute an appreciable quantity of mesotrons in the energy range between 3×10^8 to 12×10^8 ev for altitudes intermediate between that of Mount Evans and Echo Lake.

Since only mesotrons of momenta greater than

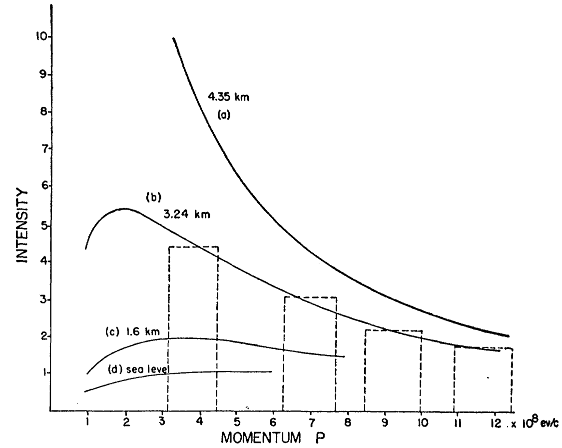

FIG. 4. Mesotron momentum spectra at several altitudes. Curve (*a*) is the measured curve for Mount Evans (4.35 km), curves (*b*), (*c*), and (*d*) are calculated from curve (*a*) for altitudes of 3.24, 1.6, and 0 km considering ionization losses in air and mesotron decay with $\epsilon_0=3\times10^{-6}$ sec. The rectangles shown in broken lines are the data of Rossi *et al.* taken at Echo Lake (3.24 km).

1×10^8 ev/c at Mount Evans can reach sea level, the spectrum as measured cannot be satisfactorily used as a basis for calculating a sea-level distribution of mesotrons. The position of the maximum, however, would be expected to occur at about 5×10^8 ev/c if mesotron production processes below 4-km altitude can be disregarded. The existing cloud-chamber experiments at sea level have tended to discriminate against such low momentum particles, producing a false maximum in the region of 10^9 ev/c.

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