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Intensity of Cosmic Rays at Low Altitude and the Origin of the Soft Component

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Absorption curves have been obtained for cosmic rays at low altitude, with absorbers of carbon, iron, and lead. The separate intensities of fast mesotrons, slow mesotrons, and electrons have been deduced from the differences between the absorption curves. The number of slow mesotrons found is much greater than the number which may have descended from the mesotrons observed at a higher altitude, thus indicating considerable production of low energy mesotrons at low altitudes. The number of electrons is much too small to allow the conclusion that all of the energy of decaying mesotrons goes into shower production. Unless the lifetime-to-mass ratio for mesotrons is larger than presently accepted values, the results favor the conclusion that *less than half* of the energy of the mesotrons goes to the electron component.

INTRODUCTION

NEAR the base of the atmosphere or under any very heavy absorber, almost the entire electron component of cosmic rays must have its origin from decay and collision processes of mesotrons, chiefly from the decay. Thus the relative intensity of mesotrons and electrons at low altitude (or under a heavy absorber) may be used to furnish information regarding mesotron decay. This has been pointed out by Euler and Heisenberg,[1] who found the existing data in accord with a rough calculation based on the assumption that the mesotron decays into an electron and a neutrino with a lifetime of 2 microseconds. More recently, Nelson[2] was able to conclude, on the basis of data taken by Neher and Stever,[3] that the relative intensities were consistent with a lifetime of 2.8 microseconds, again providing that only half of the mesotron energy goes to the electron component. The relative intensities reported by Nielsen, Ryerson, Nordheim, and Morgan[4] have led Nordheim[5] to conclude that probably *less* than half of the mesotron energy goes into shower production. But this conclusion was based on a very small value of the mesotron lifetime (1.25 microseconds), and would have been different if a lifetime of 2 microseconds or more had been assumed.

The definiteness of the above conclusions has been limited both by experimental difficulties in determining the ratio of electron and mesotron intensities, and by inaccuracies in the theories used to predict the number of electrons which should be observed as a result of mesotron decay and collision processes. Recent additions to these theories, made by Rossi and Greisen,[6] Rossi and

[1] H. Euler and W. Heisenberg, Ergeb. d. exakt. Naturwiss. **17**, 1 (1938).
[2] E. Nelson, Phys. Rev. **58**, 771 (1940).
[3] H. V. Neher and H. G. Stever, Phys. Rev. **58**, 766 (1940).
[4] W. M. Nielsen, C. M. Ryerson, L. W. Nordheim, and K. Z. Morgan, Phys. Rev. **59**, 547 (1941).
[5] L. W. Nordheim, Phys. Rev. **59**, 554 (1941).
[6] B. Rossi and K. Greisen, Phys. Rev. **61**, 121 (1942).

Klapman,[7] and Richards and Nordheim,[8] have made it possible to calculate more accurately the number of electrons which should be observed above certain energy limits. The present experiments were designed so as to eliminate some of the experimental uncertainty in the ratio of the two intensities.

Most of the experimental difficulties in determining the relative intensity of mesotrons and electrons (from counting rates in Geiger-Müller counters below different amounts of absorber) arise from the comparatively small value of the electron intensity. Since one must rely on small differences between large counting rates, the statistical errors as well as all small systematic errors become important. The effect of meteorological changes (pressure, temperature, distribution of air mass) is great, and the number of low energy mesotrons stopped by the absorbers must be determined. The effect of side showers incident upon a counter telescope creates a significant error, and the transition effects observed as the absorber is changed become important. Moreover, the fraction of the electrons recorded depends strongly on the energy limit set by the apparatus, which must therefore be known.

EXPERIMENTAL ARRANGEMENT

The arrangement of counters used for the principal measurements is shown in Fig. 1. The fourteen counters arranged in a semicylinder were

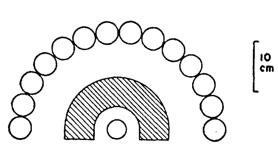

FIG. 1. Counter arrangement used in principal measurements.

60 cm long and were all connected in parallel. The central counter was 20 cm long. The principal measurements were of the coincidence rate between the central counter and the outer ones, as different absorbers were placed between the counters. Since the outer counters cover almost the entire solid angle above the central counter, the rates obtained give an intensity integrated over all angles. This serves a twofold purpose: (1) The error due to side showers is eliminated, since we wish to record the rays traversing the central counter in all directions, and (2) the counting rate is high, so that a high statistical accuracy may be obtained in a comparatively short time.

The absorbers used were cylindrical in shape. The energy limits set for electrons by the smallest absorbers were determined with fair precision by constructing these absorbers of a material of low atomic number, carbon (for which the "straggling" in the energy loss is small). Throughout the measurements with other absorbers (iron and lead), a central absorber of carbon was kept in place, so that only those electrons were recorded which emerged from the iron or lead with an energy of about 10^7 ev.

The errors in the counting rates, due to chance coincidences and inefficiency of the counters, were very small (a few tenths of a percent) and were determined by auxiliary measurements of the resolving time of the apparatus and the inefficiency of the counters. Other more serious sources of error are discussed in detail below.

DEVIATIONS DUE TO METEOROLOGICAL CHANGES

A simple correction for pressure and temperature changes cannot be made, since the cosmic-ray intensity depends on the distribution of air mass and temperature above the apparatus, more than on the values of pressure and temperature at any one point. Therefore an attempt was made to obtain an empirical correction simultaneously for all meteorological fluctuations, by using the deviations from the average of two "standard" rates, which were taken repeatedly during the running of the experiment, on alternate nights, for periods of more than 12 hours. These were the rate with the maximum lead absorber and the rate with only a small thickness of carbon as absorber. The statistical errors in the individual runs were less than 0.5 percent.

The "standard" rates were utilized as follows. Since the rates had been taken so often, it could be assumed that the simple averages were the

[7] B. Rossi and S. J. Klapman, Phys. Rev. **61**, 414 (1942).

[8] J. A. Richards, Jr., and L. W. Nordheim, Phys. Rev. **61**, 735 (1942). We are indebted to the authors for communicating their numerical results to us.

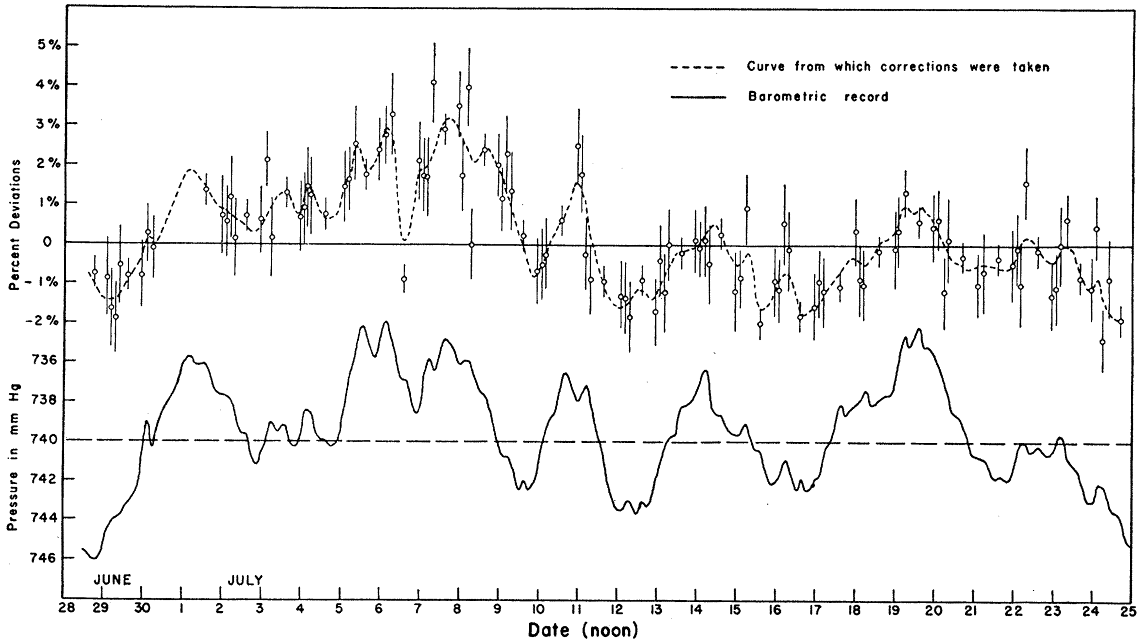

FIG. 2. Percent deviations due to meteorological changes.

correct rates for the average environmental conditions. The percent deviations of the individual runs from the average rates were plotted against the mean time at which the individual rates were obtained. In spite of the fact that the rates with the maximum lead absorber included only mesotrons, while the rates with the small carbon absorber included also the electron component, there was nothing to indicate that the two graphs of percent deviations against time should not be superposed; therefore, the points taken with both absorbers were plotted together, giving a graph of percent deviation from the mean which should be valid for all the intermediate absorbers as well. The corrections for the rates taken with the other absorbers were read from this graph, according to the mean time at which the rates were obtained. From these corrected rates, the average rate was computed for each absorber used.

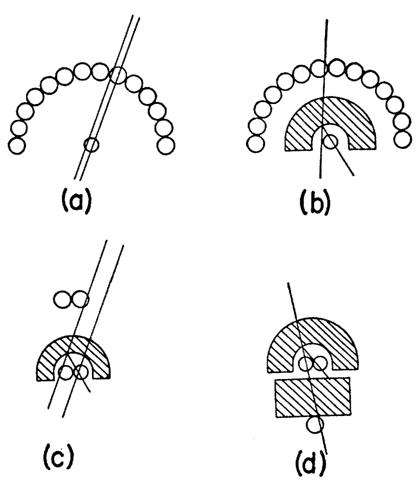

FIG. 3. Illustrating errors due to showers and secondary particles, and methods of correction.

In Fig. 2 we have plotted the percent deviations from the average, including the individual runs not only with the "standard" absorbers but with the intermediate absorbers as well. For comparison, we have also drawn the barometric record for the same period of time. It is obvious from this graph that changes in cosmic-ray intensity are not always exactly "in phase" with corresponding changes in barometric pressure, and that the same change in barometric pressure does not always accompany the same change in cosmic-ray intensity.

EFFECT OF INCIDENT SHOWERS AND SECONDARIES GENERATED IN THE ABSORBER

Figure 3a illustrates the error associated with showers incident upon the apparatus, which leads

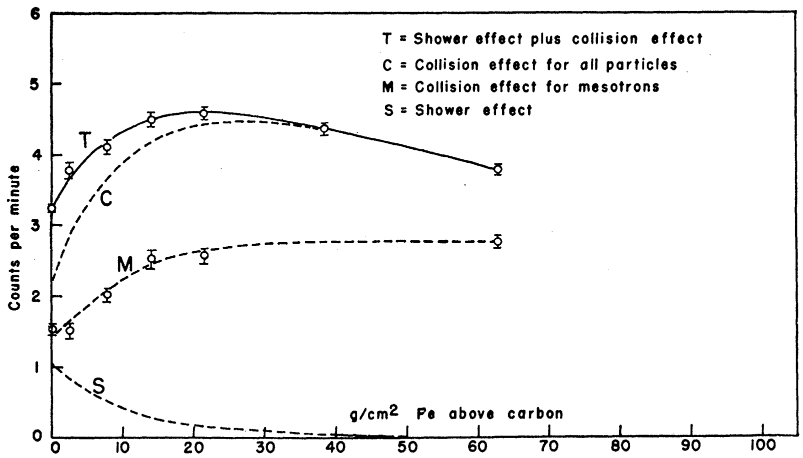

FIG. 4a. "Shower" and "collision" effects in iron.

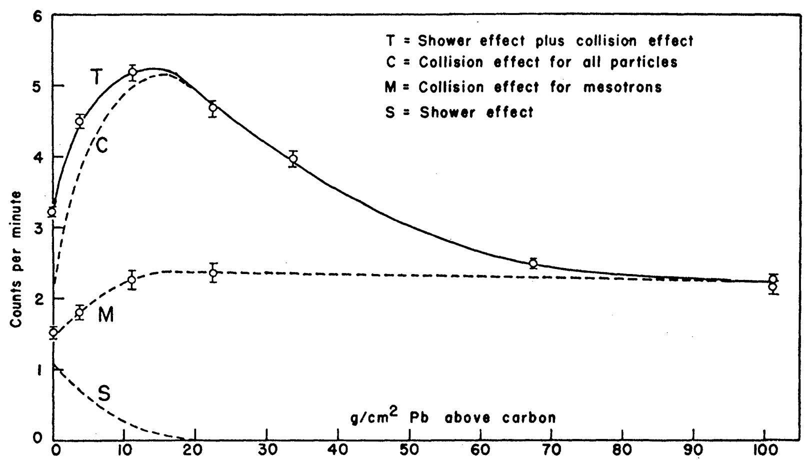

FIG. 4b. "Shower" and "collision" effects in lead.

to an underestimate of the number of electrons striking the apparatus. Except for very small absorbers, this effect is unimportant, because there is no error unless both particles have enough energy to penetrate the absorber. Even for small absorber thicknesses the effect is not very large, because of the great spread of air showers. For brevity we shall refer to this effect as the "shower effect."

Figure 3b illustrates an error in the opposite direction, due to secondary particles generated in the absorber. This is a sort of "transition effect" which may be described as an increase in effective size of the central counter due to the presence of the absorber. We shall refer briefly to this effect as the "collision effect," because it is largely caused by collision electrons knocked out of the absorber by mesotrons.[9]

In order to determine the error due to the shower and collision effects, an auxiliary experiment was performed with counters arranged as in Fig. 3c. The two upper counters were connected in parallel, and threefold coincidences between these and the lower counters were recorded as a function of absorber thickness, with the same absorbers as were used in the principal measurements. For comparison, we also recorded the

[9] Admittedly the term "collision effect" is not entirely appropriate, since a large part of this effect is caused by showers generated in the absorber. The only real distinction between the "shower" and "collision" effects, as we have called them, lies in whether the multiplicity existed above the absorber or was caused by the absorber.

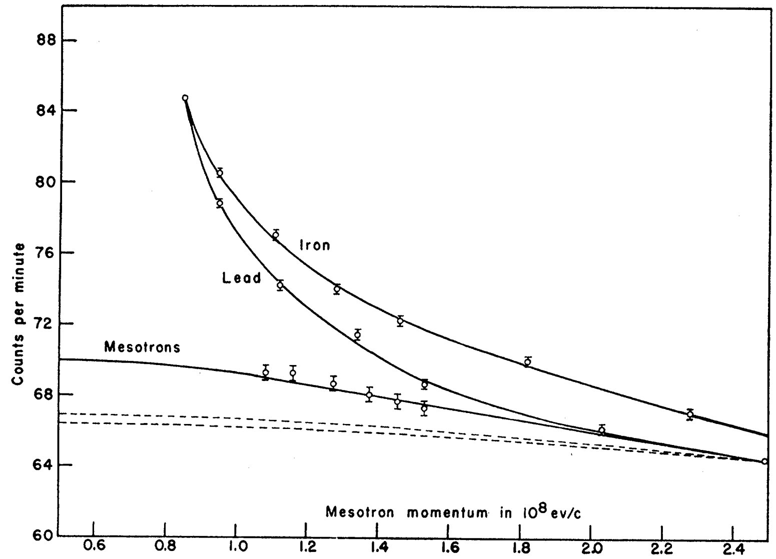

FIG. 5. Absorption curves in iron and lead.

twofold coincidence rate between the upper counters and *one* of the lower counters. It can easily be shown that the threefold coincidence rate obtained in this experiment is proportional to the *sum* of the errors due to the shower effect and the collision effect.[10] The proportionality constant is the ratio of the coincidence rate in the principal experiment to the twofold coincidence rate in this auxiliary experiment, which ratio had the same value (3.42), within statistical errors, for all of the absorbers used.

TABLE I. Corrections to counting rates, and final corrected rates.

Absorber	Average rate corrected for meteorological changes only	Net correction for "collisions" and "showers"	Net corrections for inefficiency and chance coincidences	Corrected rate
None	90.3 min.$^{-1}$	+0.3 min.$^{-1}$	+0.1 min.$^{-1}$	90.7 min.$^{-1}$
1.36 g/cm²C	87.8	−0.5	+0.1	87.4
2.84 g/cm²C	85.7	−1.1	+0.1	84.7
4.2 g/cm²C	83.7	−1.5	+0.1	82.3
6.1 g/cm²C	81.6	−1.8	+0.1	79.9
2.84 g/cm²C				
+2.5 g/cm²Fe	82.4	−2.0	+0.1	80.5
+7.8 g/cm²Fe	80.1	−3.1	+0.1	77.1
+14.0 g/cm²Fe	77.8	−3.9	+0.1	74.0
+21.4 g/cm²Fe	76.3	−4.2	+0.1	72.2
+38.2 g/cm²Fe	74.2	−4.3	+0.1	70.0
+62.8 g/cm²Fe	70.8	−3.8	+0.1	67.1
2.84 g/cm²C				
+3.8 g/cm²Pb	81.8	−3.1	+0.1	78.8
+11.3 g/cm²Pb	78.9	−4.8	+0.1	74.2
+22.5 g/cm²Pb	76.0	−4.6	+0.1	71.5
+33.8 g/cm²Pb	72.6	−4.0	+0.1	68.7
+67.5 g/cm²Pb	68.6	−2.5	+0.1	66.2
+101 g/cm²Pb	66.7	−2.3	+0.1	64.5

In Figs. 4a and 4b we have plotted the results of this auxiliary experiment. The uppermost curve (T) represents the sum of the errors due to shower and collision effects, determined as explained in the above paragraph. The correction to be applied to the counting rates in the principal experiment, however, is the difference between these two errors, rather than the sum. Fortunately the shower effect is small and decreases rapidly as the absorber thickness is increased. From the results obtained with very small absorbers in the experiment described above, it was possible to estimate the magnitude of this effect for zero absorber, while the variation of the effect with absorber thickness could be roughly calculated; such estimates (admittedly not exact) have led to the curves S, the lowest dashed curves in Figs. 4a and 4b. Curve C represents the difference between the ordinates of T and S; i.e., the collision effect alone. The corrections applied to the

[10] This conclusion rests on two assumptions: (1) That for two particles striking the apparatus simultaneously in such a direction that one of them penetrates one of the lower counters, it is equally likely that the second particle should penetrate the same counter or an identical counter adjacent to the first; and (2) that particles which pass by the central counter at distances greater than a counter diameter (4 cm) do not produce secondaries which discharge the counter. The first assumption is justified by the large spread of air showers; the second by the small average spread of showers in iron or lead.

counting rates are given by the differences between the ordinates of C and S. The curves M in Figs. 4a and 4b represent the collision effect for mesotrons alone, as determined with the arrangement shown in Fig. 3d.

In Table I we list the absorber thicknesses used in this experiment, and the corresponding counting rates, together with the corrections applied to the rates.

SEPARATION OF MESOTRON AND ELECTRON INTENSITIES

The method of obtaining the separate intensities of mesotrons and electrons from the counting rates resembles a method recently used by Auger[11] in analyzing measurements taken at a higher altitude. The momentum limits for mesotrons were calculated, corresponding to all of the absorbers used in the experiment, from the range-momentum relations given by Rossi and Greisen.[12] (In determining the ranges, the average absorber thicknesses were used, taking into account the differences in absorber thickness for mesotrons arriving in different directions.) The counting rates obtained with the iron and lead absorbers were plotted as a function of these momentum limits, yielding the two upper curves in Fig. 5. At each abscissa on this graph, the ordinate representing the mesotron intensity must have been the same for both the iron and the lead absorber. The difference between the curves arises from the fact that more electrons penetrate the iron; i.e., thicknesses of iron and lead which are equivalent for mesotrons are not equivalent for electrons. In fact, for electrons of energy large compared with the critical energies (25 Mev in iron, 7 Mev in lead), the iron and lead are equivalent for electrons in *radiation lengths* (14.4 g/cm^2 in iron, 5.9 g/cm^2 in lead). Thus in order to penetrate the maximum thickness of iron, the electrons must traverse, on the average, in addition to the carbon, only 4.75 radiation lengths of iron, while the corresponding thickness of lead is 15.8 radiation lengths.

It was assumed that no electrons penetrate the thickness of lead equivalent (for mesotrons) to the maximum thickness of iron.[13] The difference between the two absorption curves at this abscissa represents the number of electrons which can penetrate a smaller thickness of lead (the thickness which is equivalent for electrons to the maximum thickness of iron). By subtracting this difference from the lead absorption curve at the appropriate abscissa, one point is obtained on an extrapolated curve representing the total mesotron intensity (see Fig. 5). The difference between this extrapolated curve and the iron absorption curve at another thickness of iron may be subtracted from the lead absorption curve at a still smaller abscissa. By proceeding in this way, the six points on the "Mesotron" curve in Fig. 5 have been obtained. We are assisted in drawing the curve by the fact that it must be tangent to the lead absorption curve at the greatest thicknesses, and must become horizontal as the momentum approaches zero (not only because of the increase in the decay probability per cm as the velocity decreases, but also because of the increase in the energy loss).

TABLE II.

Absorber	Average energy limit for electrons (Mev)	Total number of electrons per min.	Electrons from collision processes	Electrons from remaining sources
None	3.4	20.8	7.6	13.2
1.36 g/cm^{2}C	6.4	17.6	5.6	12.0
2.84 g/cm^{2}C	10.0	15.1	4.2	10.9
4.2 g/cm^{2}C	13.6	12.8	3.4	9.4
6.1 g/cm^{2}C	18.9	10.8	2.7	8.1
2.84 g/cm^{2}C +62.8 g/cm^{2}Fe	350	2.0	0.0	2.0

The only questionable part of the above procedure is the determination of thicknesses of iron and lead which are exactly equivalent for electrons. Actually, different absorbers can never be equivalent for all electrons, because of the difference in critical energies. However, the carbon absorber kept permanently under the iron and lead removes from consideration the many electrons of energy below 10^7 ev which emerge from the lead. If the energy limit set by the carbon absorber had been somewhat higher (several times the critical energy in iron, 25 Mev), we should have been able to say the iron and lead

[11] P. Auger, Phys. Rev. **61**, 684 (1942).

[12] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

[13] This assumption is justified by the graphs in Fig. 4b, which show that at this thickness the transition effect for all particles traversing the lead agrees with the transition effect for mesotrons alone.

absorbers were exactly equivalent in radiation lengths; as it is, this is still true after such thicknesses of iron and lead that the energy limit has been so increased. Thus, the average energy loss of the electrons barely capable of penetrating the absorber, in the first radiation length of iron, is the same as that in the first 1.6 radiation lengths of lead; beyond these thicknesses, the iron and lead are equivalent in radiation lengths. Hence, for values of x greater than 1, we have assumed x radiation lengths of iron equivalent to $x+0.6$ radiation lengths of lead.

From the "Mesotron" curve in Fig. 5 we have obtained the counting rate due to mesotrons corresponding to each of the absorbers used in this experiment; in particular for the carbon absorbers, for which the average energy limits set for electrons could be calculated. By subtracting the counting rates due to mesotrons from the total counting rates, we have obtained the counting rates due to electrons, which are given in Table II. The number of electrons penetrating the maximum iron absorber has also been given, for which the approximate energy limit has been calculated with the Snyder-Serber theory.[14]

MESOTRONS DESCENDED FROM A HIGHER ALTITUDE

Under the assumption that practically no electrons penetrate the maximum lead absorber,[13] the counting rate with this absorber gives the intensity of "fast" mesotrons (i.e., mesotrons of momentum above 2.5×10^8 ev/c, the average limit set by this absorber). If the number of mesotrons at Ithaca with momentum below this limit can be calculated, we have an alternative method of obtaining the total number of mesotrons and, hence (by subtraction from the absorption curves), the number of electrons. Provided that no mesotrons are produced between the two elevations, we may calculate the number of low energy mesotrons at Ithaca as the number which have descended from a higher elevation, where they had a greater energy.

Mesotrons of momentum between 0 and 2.5×10^8 ev/c at Ithaca (275-meters elevation) would correspond to mesotrons with momentum between 6.6 and 8.1×10^8 ev/c at Echo Lake (3240-meters elevation), where a differential momentum spectrum of mesotrons, including this range, has been obtained by Rossi, Greisen, Stearns, Froman, and Koontz.[15] By using this momentum spectrum, together with the probability of survival of the mesotrons between the two elevations,[16] we have calculated the number of slow mesotrons which have survived to reach Ithaca from the elevation of Echo Lake. By adding these to the number of fast mesotrons, we have obtained the dashed curves shown in Fig. 5, which should represent the total mesotron intensity. The two curves correspond to calculations made with two different values of the lifetime-to-mass ratio for mesotrons, 8.4×10^{-4} cm-c/ev (upper curve) and 6.7×10^{-4} cm-c/ev (lower curve), between which the correct value probably lies. The value 8.4×10^{-4} cm-c/ev is taken from the measurements of Rossi and collaborators,[15] but may be somewhat too high if mesotron production is an important process at low elevations. A recent direct measurement by Rossi and Nereson[17] indicates that the mesotron lifetime is about 2.2 microseconds; this together with a mesotron mass of 160 electron masses would indicate 8.4×10^{-4} cm-c/ev for the lifetime-to-mass ratio, in agreement with the other measurements, but with a mesotron mass of 200 electron masses indicates 6.7×10^{-4} cm-c/ev for the lifetime-to-mass ratio.

The graphs in Fig. 5 show that this calculation of the number of slow mesotrons is incorrect. In the first place, it yields a graph of total mesotron intensity which is not tangent to the absorption curve in lead at the largest thicknesses. Secondly, it predicts that the number of slow mesotrons is only 3 percent of the total number of mesotrons, while the differences between the absorption curves in iron and lead indicate that the number of slow mesotrons is 8 percent of the total number. From this discrepancy, we may conclude that more than half of the slow mesotrons observed at Ithaca have originated in the air below 3240-meters elevation.

It should be observed that this conclusion has

[14] H. Snyder, Phys. Rev. **53**, 960 (1938); R. Serber, Phys. Rev. **54**, 317 (1938).

[15] B. Rossi, K. Greisen, J. C. Stearns, D. K. Froman, and P. G. Koontz, Phys. Rev. **61**, 675 (1942).

[16] See B. Rossi, Rev. Mod. Phys. **11**, 296 (1939).

[17] B. Rossi and N. Nereson, Phys. Rev. **62**, 417 (1942).

little bearing on the place of origin of the fast mesotrons. If one takes into account not only the decay but also the decrease in rate of mesotron production with increasing atmospheric depth, a rough calculation indicates that most of the high energy mesotrons observed near sea level should have originated near the top of the atmosphere, while most of the low energy mesotrons should have originated near the place of observation.

ABSOLUTE INTENSITIES

From the counting rates given above, it is possible to obtain, by a purely geometrical calculation, the absolute integrated intensities of mesotrons and electrons at Ithaca. The integrated intensity to which the counting rates are most closely related is the one which is connected with the specific ionization, and which gives the number of particles per minute crossing a sphere of unit cross section. In terms of the absolute directional intensity $I(\theta)$ and the zenith angle θ, this integrated intensity is defined as

$$J=2\pi\int_0^{\pi/2}\sin\theta I(\theta)d\theta.$$

Because of the cylindrical shape of the counters, the rates obtained in this experiment do not yield J directly, but yield an elliptic integral of the directional intensity, which may be written as

$$R=2\pi\int_0^{\pi/2}\sin\theta I(\theta)F(\theta)d\theta.$$

$F(\theta)$ is a slowly varying factor, the total variation in which is less than 30 percent of its value at $\theta=0$. Hence we may write $R=KJ$, where K is a constant which depends slightly on the zenith-angle variation of the cosmic-ray intensity, and may be found from a tedious calculation involving the dimensions of the apparatus. In the calculation of K, account is taken of the fact that the outer counters in the present experiment did not completely cover the solid angle above the central counter; however, only a few percent of the particles were missed in this way, because of the small number arriving at large zenith angles. Because the electron intensity has a somewhat steeper zenith-angle dependence than has the mesotron intensity, we have obtained slightly different values of K for electrons and for mesotrons ($K=59.6$ for mesotrons, 61.4 for electrons). The absolute integrated intensities thus calculated are listed in Table III. The errors given include not only the statistical errors but also an estimate of the likely errors which may have arisen in the method of computation.

TABLE III. Absolute integrated intensities of mesotrons and electrons.

Component of cosmic rays	Particles per cm^2 per min.
Mesotrons above 2.5×10^8 ev/c	1.082 ± 0.007
Mesotrons above 0.5×10^8 ev/c	1.175 ± 0.012
Electrons above 3.4 Mev	0.339 ± 0.015
Electrons above 6.4 Mev	0.287 ± 0.014
Electrons above 10.0 Mev	0.246 ± 0.012
Electrons above 13.6 Mev	0.208 ± 0.014
Electrons above 18.9 Mev	0.176 ± 0.015
Electrons above 350 Mev	0.033 ± 0.008

ELECTRONS ARISING FROM COLLISION PROCESSES OF MESOTRONS

The number of electrons of energy above 10^7 ev in equilibrium with the mesotrons at sea level, as a result of the collision processes, has been calculated accurately by Rossi and Klapman,[7] who obtained the result that the number of electrons was 6.7 percent of the number of mesotrons with momentum above 3×10^8 ev/c. This would be about 6.6 percent of the mesotrons with momentum above 2.5×10^8 ev/c, the limit set by the maximum absorber in the present experiment. Thus the counting rate for collision electrons above 10^7 ev (which corresponds to the energy limit set by one of our carbon absorbers) should be 4.2 per minute.

An approximate method of calculation of the number of collision electrons with energy above other limits has been suggested to the author by Professor Rossi and rests on the conservation of energy. Since the collision electrons are in equilibrium with the mesotrons, the energy given to electrons of energy above E in each g/cm^2 must be equal to the energy dissipated by them in each g/cm^2. This energy is lost in two ways: (1) by electrons drifting through the boundary E to lower energies, each taking away an energy E, and (2) by collision and radiation losses of electrons which remain above the boundary E. The last term is very closely approximated by the number of electrons of energy above E times the energy loss of electrons of energy E. The number

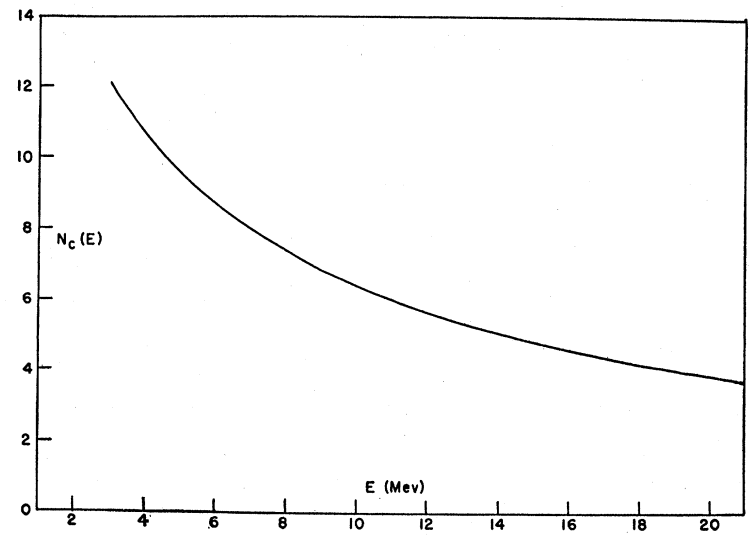

FIG. 6. Electrons arising from collision processes of mesotrons in air. $N_c(E)$ = number of electrons of energy above E in equilibrium with the mesotrons, per 100 mesotrons of momentum above 2.5×10^8 ev/c.

which drift through the boundary to lower energies is equal (under the same approximations) to the number of new electrons added to the group by mesotron collisions. This term, as well as the energy given to the electrons of energy above E, may be calculated from the collision probabilities of mesotrons and integrated over the momentum spectrum of mesotrons given by Blackett.[18] The results of such calculations are presented as a function of E in Fig. 6.

The accuracy of these calculations may be tested by comparing the result for $E=10^7$ ev with the value obtained for this energy by the more accurate calculations of Rossi and Klapman. The present calculations give $N_c(10^7)=6.4$ per 100 fast mesotrons, while those of Rossi and Klapman give $N_c(10^7)=6.6$, in very close agreement.

The counting rates due to collision electrons, corresponding to the carbon absorbers used in this experiment, are listed in Table II.[19] By subtracting the collision electrons from the total electron intensity, we have obtained the electron intensities listed in the last column of that table. The principal source of these remaining electrons must be the decay of mesotrons; but regardless of whether or not some of the electrons have other origins (e.g., primary electrons or radiation by mesotrons), the numbers listed in this column must be *at least* as great as the numbers of electrons arising from mesotron decay.

ELECTRONS ARISING FROM DECAY OF SLOW MESOTRONS

The primary electrons arising from decay of mesotrons with momentum below 2.5×10^8 ev/c have energies of the same order as the critical energy in air; hence the shower theory cannot be applied to calculate the number of electrons to which they give rise. Therefore we have used instead the approximate method of calculation which was used above for the collision electrons. Because the energy spectrum of the decay electrons is not as steep as that of the collision electrons, the approximations are not as good; but because of the small number of slow mesotrons, a slight error in this calculation is of no significance. For the momentum spectrum of slow mesotrons, over which an integration is required, we have used the results deduced in the present paper from the differences between the absorption curves in iron and lead. The results of the

[18] P. M. S. Blackett, Proc. Roy. Soc. **159**, 1 (1937).

[19] These have been obtained from the graph in Fig. 6 by multiplying the number of electrons per fast mesotron by the counting rate due to fast mesotrons in the present experiment. The results have been corrected in the ratio 6.6/6.4 to give exact agreement at $E=10^7$ with the calculations of Rossi and Klapman, which were considered more accurate than the present calculations.

TABLE IV. Electrons arising from mesotron decay.

Energy limit for electrons (Mev)	Assumed decay products: 1 electron, 1 neutrino $\tau_0/\mu=6.7\times10^{-4}$ cm-c/ev S	F	T	$\tau_0/\mu=8.4\times10^{-4}$ cm-c/ev S	F	T	Assumed products: 1 electron, 2 neutrinos $\tau_0/\mu=6.7\times10^{-4}$ T	$\tau_0/\mu=8.4\times10^{-4}$ T
3.4	2.5	19.5	22.0	2.0	15.6	17.6	14.7	11.7
6.4	2.2	17.9	20.1	1.8	14.3	16.1	13.4	10.7
10.0	2.0	16.4	18.4	1.6	13.1	14.7	12.3	9.8
13.6	1.8	15.3	17.1	1.45	12.2	13.7	11.4	9.1
18.9	1.6	14.0	15.6	1.3	11.2	12.5	10.4	8.3
350	0.0	2.3	2.3	0.0	1.8	1.8	1.5	1.2

Legend: S = predicted counting rate due to electrons arising from decay of slow mesotrons; F = predicted counting rate due to electrons arising from decay of fast mesotrons; $T=S+F$ = total predicted counting rate due to electrons arising from mesotron decay.

calculations are listed in Table IV, corresponding to the two values of the lifetime-to-mass ratio with which the calculations have been made (see discussion above in the section on mesotrons descended from a higher altitude). These calculations have been made under the assumption that the decay products of the mesotron are an electron and a neutrino. If the decay products are an electron and a photon, the numbers should be multiplied by approximately 2; while if the mesotron decays into an electron and two neutrinos, the results should be multiplied by $\frac{2}{3}$.

ELECTRONS ARISING FROM DECAY OF FAST MESOTRONS

Since most of the primary electrons arising from the decay of fast mesotrons have energies large compared with the critical energy in air, the shower theory can be applied to calculate the number of electrons to which they give rise. It has been shown by Rossi and Greisen[12] that if one neglects the decrease in the rate of production of the primary electrons over a distance equal to the maximum range of the showers, then the number of electrons of energy above E in equilibrium with the mesotrons is given by the integral track length of all electrons above energy E produced per g/cm^2 by the mesotrons. In another article,[6] the same authors have shown that the variation in the rate of production of the primary decay electrons can be taken into account by evaluating the track length for the electrons produced per g/cm^2 at a distance of 130 g/cm^2 above the place of observation.

The track length for $E=0$ is obtained simply from the conservation of energy as 43 E_0/ϵ, where E_0 is the energy going to decay electrons per g/cm^2, and $\epsilon/43$ is the ionization loss per g/cm^2, ϵ being the critical energy, and 43 g/cm^2 being the radiation length in air. For other energies, we have used the accurately known track length for $E=0$ together with the relative track lengths (or energy distribution at the maximum of a shower) recently calculated by Richards and Nordheim.[8] The track length for $E=10^7$ ev, calculated by Rossi and Klapman,[7] agrees very closely with the corresponding value obtained by Richards and Nordheim, the latter value being higher by about 3 percent.

The energy E_0 going to decay electrons per g/cm^2, due to the disintegration of fast mesotrons, is given by $E_0=\frac{1}{2}(\mu/\tau_0)(N/\rho)$ (where ρ is the density of air, N is the number of fast mesotrons, and τ_0/μ is the lifetime-to-mass ratio), under the assumption that the disintegration products are an electron and a neutrino. If the mesotron decays into an electron and a photon, E_0 should be twice as large; if into an electron and two neutrinos, E_0 should be $\frac{2}{3}$ as large. E_0 must be evaluated at 130 g/cm^2 above the place of observation; hence the values of N at 130 g/cm^2 above Ithaca were read from a graph of mesotron intensity *vs.* elevation recently obtained by the author.[20] Data were available at four different zenith angles, so that an integration over zenith angle could be performed, as was required for comparison with the data of this experiment. Thus we have obtained the numbers in Table IV, which represent the hypothetical counting rates due to electrons arising from decay of fast mesotrons.

CONCLUSIONS

The total numbers of electrons arising from decay, given in Table IV, should be comparable

[20] K. Greisen, Phys. Rev. **61**, 212 (1942).

with the counting rates listed in the last column of Table II; at any rate, they should be *no larger* than those counting rates. Hence it is impossible that the mesotron should decay into a photon and an electron, for in that case the counting rate due to electrons arising from decay would have to be three times what was observed; in fact, it would have to be 50 percent greater than the total difference in counting rate between the minimum absorber (only the counter walls) and the maximum absorber (including 101 g/cm^2 of lead).

Because of the indirect way in which the counting rates listed in the last column of Table II were obtained, they cannot be considered very accurate. However, considering all the possible sources of error, it is unlikely that any of these numbers should be in error by as much as 3 counts per minute, or that the last of the numbers should be in error by as much as 0.5 counts per minute. Hence we may conclude that the results also discourage the hypothesis that the decay products are an electron and a neutrino. At any rate, if these should be the decay products, the results indicate that the lifetime-to-mass ratio for mesotrons is at least as large as 8.4×10^{-4} cm-c/ev. Thus, if one accepts the value of the lifetime (2.2 microseconds) recently obtained by Rossi and Nereson,[17] the mass of the mesotron must be no larger than 160 electron masses.

In general, however, the results favor the hypothesis that *less* than $\frac{1}{2}$ of the energy of decaying mesotrons goes to the electron component. They would be in agreement with a decay into an electron and two neutrinos, for instance, in which case the spin of the mesotron might be $\frac{1}{2}$ but not 0 or 1, and only $\frac{1}{3}$ of the mesotron energy would go into shower production.

It has been suggested[1,21,22] that some of the mesotrons may disappear by another process other than radioactive decay and, hence, without contributing to the electron component. If this were an important process in the atmosphere, it might reconcile the disintegration into an electron and a neutrino with the small number of electrons observed. However, because of the small density of the atmosphere, and because most of the electrons should arise from disintegration of mesotrons of great momentum, we do not think that the suggested process can affect the conclusions discussed above.

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[21] S. Tomonaga and G. Araki, Phys. Rev. **58**, 90 (1940).
[22] F. Rasetti, Phys. Rev. **60**, 198 (1941).