Cosmic-Ray Investigations on Mt. McKinley*

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Three cosmic-ray experiments were carried out on Mt. McKinley (Alaska) at an altitude of 18,100 feet. The first experiment measures the absorption curve of penetrating particles in Pb thicknesses up to 50 cm. A large number of slow mesotrons of energies around 200 Mev was found. From the measured mesotron energy spectrum on Mt. McKinley a calculation was made to determine the spectrum which would be anticipated at 14,250 feet (Mt. Evans, Colorado). The result is compared with experimental data obtained on Mt. Evans. The discrepancy between the two curves strongly indicates that an additional production of mesotrons of energies less than 400 Mev takes place in the atmosphere between these altitudes. The other two experiments at 18,100 feet investigate the production of penetrating particles by ionizing and non-ionizing radiation in lead and paraffin.

DURING the Spring of 1947 there was organized an expedition to Mt. McKinley, Alaska, one objective of which was to undertake cosmic-ray investigations at an altitude previously attainable only in short-duration plane flights. Since the conditions under which observations were made were very difficult, it was necessary to make the equipment as simple as possible. The apparatus was all assembled at the University of Chicago and dropped by parachute from an airplane at Denali Pass between the two peaks of Mt. McKinley where the high altitude camp was established. Here, H. T. Victoreen, who was in charge of the experiment, carried out the actual measurements in a hut which was located at an altitude of 18,100 feet. The temperature in the hut was kept within 3° of 10°C, despite extremely low temperatures outside.

EXPERIMENT I: ABSORPTION OF PENETRATING PARTICLES

Figure 1 shows the geometry of the first counter experiment in which the intensity of penetrating radiation at 18,100 feet was investigated. Recording apparatus measured counts from (a) the upper telescope (fourfold coincidences 1–2–3–4), (b) the lower telescope (fourfold coincidences 2–3–4–5), and (c) showers (fourfolds from the out-of-line system 1–6–3–4). The resolving time of the coincidence sets was 20 microseconds. All counters had the same dimensions, 7 in.×1 in. In successive ten-hour recording intervals various thicknesses of lead were placed at positions A, B, and C; a narrow ($1\frac{7}{8}''$) vertical column of lead plates was used to minimize scattering. The fact that the recording rate for a given total thickness of lead in a telescope remained uniform and did not depend on how that thickness was distributed between the positions A, B, and C strongly indicates that scattering played a negligible role in this experiment. The shower rate, about 6 per hour, showed little variation with the thickness or position of

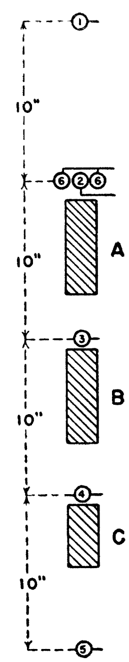

FIG. 1.

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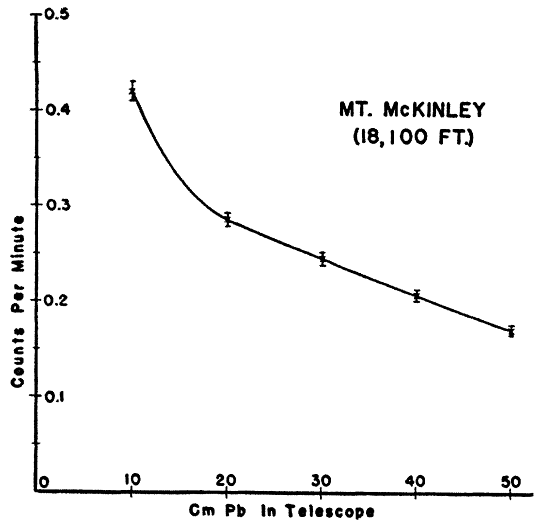

FIG. 2.

the lead plates. The counting rate of the *upper* telescope, averaged over recording intervals when it included a given total thickness of Pb, agreed in all cases within statistical error with the average rate of the *lower* telescope during recording intervals when it included the same total thickness of Pb. The intensity of penetrating particles was obtained by averaging the coincidence rate of the upper (a) and lower (b) telescopes for each case in which the thickness of lead included in the telescopes was the same, and then subtracting showers (c). The results are shown in Table I. The counts per minute are plotted in Fig. 2 against the total thickness of Pb in the telescope. The ratio of intensity through 18-cm Pb at McKinley to that in initial tests at Chicago near sea level is 3.0. This may be compared with data from balloon flights by Schein and others,[1] who find the intensity through 18-cm Pb increases by a factor of 3.1 between sea level and 18,000 feet.

EXPERIMENT II: PRODUCTION OF MESOTRONS BY NON-IONIZING RADIATION

The apparatus for direct investigation of production of penetrating particles by non-ionizing radiation in lead and paraffin is shown in the left portion of Fig. 3. It is designed to give information about radiation which is non-ionizing when incident on the apparatus from above and hence does not actuate the upper three anticoincidence counters 5, but which in interacting with the matter placed at D gives rise to a penetrating ionizing particle capable of actuating the telescope 1–2–3–4 containing 10 cm of Pb. Two anticoincidence counters are also placed on either side of the counter 1 to give additional protection against showers. Counters 1, 2, 3, and 4 are 1 in.×7 in.; all the counters 5 are 1 in.×17 in. The inefficiency of the anticoincidence arrangement was measured at Chicago to be 0.5 percent. However, initial tests at Chicago with a radium source increasing the total background rate by a factor of 12 (giving single-tube counting rates comparable to those at McKinley) indicated an inefficiency of 1.2 percent under those conditions. The counts recorded on Mt. McKinley are listed in Table II. The first entry, "mesotrons," is the number of fourfold coincidences of the telescope 1–2–3–4 with all the anticoincidence counters 5 removed, and represents the intensity of particles penetrating 10-cm Pb within the solid angle of the telescope. A recording interval (4.70 hours), equal to the time in which 1000 counts were thus registered with the anticoincidence counters removed, was used in all subsequent runs so that the resulting data can easily be read as percentage of the mesotron intensity. With various thicknesses of lead and paraffin inserted at D, the number of counts of counters 1–2–3–4 in coincidence and counters 5 in anticoincidence found during each interval are shown. Repeated values represent duplicate runs under the same conditions. The counts (about 2 percent of the total mesotron intensity) recorded with no material in position D are most probably attributable to inefficiency, since the solid angle of the telescope was completely covered by the anticoincidence counters and the chances are practically negligible for either (a) showers which could strike 1, 2, 3, 4, and none of the counters 5, or (b) mesotron production in

TABLE I.

Cm Pb	10	20	30	40	50
Counts/min.	0.420	0.285	0.244	0.206	0.170
Prob. error	±0.010	±0.007	±0.007	±0.006	±0.005

[1] Marcel Schein and D. J. Montgomery, *Problems in Cosmic Ray Research* (Princeton University Press, Princeton, New Jersey, 1946).

he counter walls or in the air gap at D. Introuction of either lead or paraffin at D changes the counting rate by an insignificantly small amount. Allowing for the statistical errors of the experiment, it can be stated that any production by non-ionizing radiation of mesotrons capable of penetrating 10-cm Pb, at a rate greater than 3 percent of the total mesotron intensity, certainly could not have escaped detection. Hence, for the number of mesotrons capable of penetrating 10-cm Pb produced by non-ionizing radiation in up to 6 cm of Pb and paraffin at 18,100 feet, we may set an upper limit of 3 percent of the total mesotron intensity through 10-cm Pb.

Two additional runs were carried out to investigate multiple production of mesotrons by non-ionizing radiation. With 6-cm Pb at D in Experiment II, the two counters 6 connected in parallel were added as shown below the bottom absorber, and counts with 1–2–3–4–6 in coincidence and counters 5 in anticoincidence were recorded. The very low counting rate (7 and 1 counts per 4.7 hour interval, respectively) under these conditions indicates the excellent shower-protecting ability of the anticoincidence arrangement. In view of the results above in which single particles were recorded; it is not surprising that no measurable effect of multiple production was found.

EXPERIMENT III: PRODUCTION OF MESOTRONS BY IONIZING RADIATION

The apparatus designed to investigate the production of mesotrons by ionizing radiation is shown in the right section of Fig. 3. The two counters 3 and 4 on either side are just clear of the line of counters 1, 2, and 5 so that it is impossible for one or even two particles traveling in a straight line to activate all the counters. All five counters can be activated, however, by an incident ionizing particle which, in addition to being able either itself to penetrate the block E plus 10-cm Pb or to give rise in the block E to an ionizing particle capable of penetrating 10-cm Pb, can *also* produce in the block E at least two ionizing particles with an angular spread suitable to actuate counters 3 and 4. Since there is no shower protection, a shower of five particles can also cause a coincidence of all five counters. The fivefold coincidences 1–2–3–4–5 recorded with various thicknesses of lead and paraffin at E are shown in Table III. The counts for each thickness of absorber cover a ten-hour period during which about 780 penetrating particles would have passed through the vertical telescope 1–2–5. Comparison with the shower rate in Experiment I leads one to expect here a shower rate of the same order of magnitude as

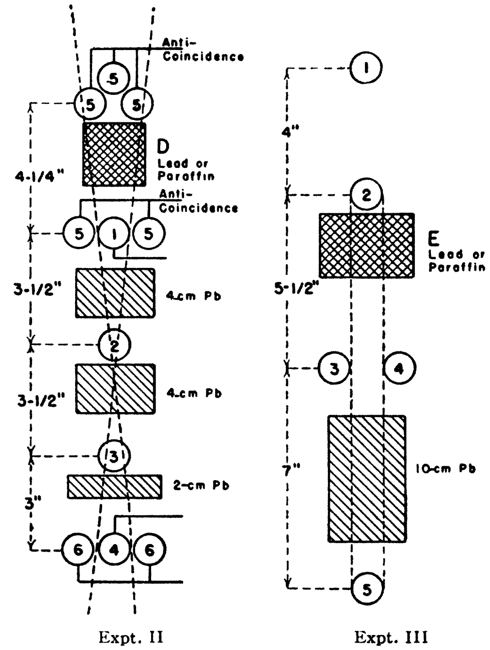

FIG. 3.

TABLE II.

("mesotrons" Absorber at D	Counts (4.7 hrs.) 1000)
No absorber	18, 21
1-cm Pb	17
2-cm Pb	17, 20
6-cm Pb	24, 24
3-cm paraffin	21
6-cm paraffin	22

TABLE III.

Absorber at E	Counts (10 hrs.)
No absorber	49
1-cm Pb	71
2-cm Pb	56
5-cm Pb	46
No absorber	43
2.5-cm paraffin	45
5-cm paraffin	51

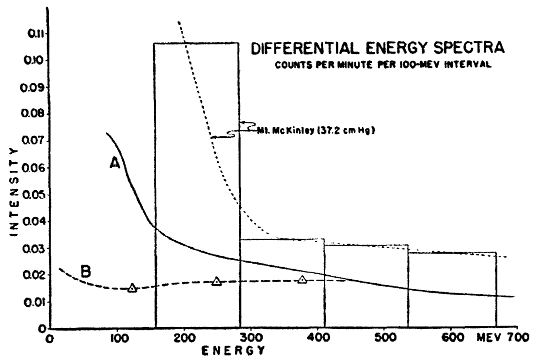

FIG. 4. The blocks and dotted curve represent the differential mesotron energy spectrum obtained on Mt. McKinley. Curve A is the Mt. Evans (45.7-cm Hg) spectrum from data of D. Hall. Curve B is the spectrum anticipated at 45.7-cm Hg, calculated by the diffusion of the mesotrons of the McKinley spectrum.

the rates recorded in Table III. The rates (49, 43) with no absorber at E must have been entirely due to showers, and the rates when an absorber was introduced can probably be attributed to the same cause.

DIFFERENTIAL ENERGY SPECTRUM

From the absorption curve of Experiment I one can obtain a differential energy spectrum for the penetrating radiation. Only a negligible number of electrons can have been included in the curve of Fig. 2. Electrons of energy sufficient to penetrate 10-cm Pb or more should occur at this altitude predominantly in the core of air showers which are dense enough so that if they actuated circuit (a) or (b) they would also have tripped the shower circuit (c). The shower rate was subtracted before the absorption curve was plotted. A check on the absence of an appreciable high energy electron component was afforded by the other two experiments. In Experiment III above, electrons able to penetrate 10-cm Pb would in passing through the block E have given rise to other ionizing particles with a probability high enough to have been detected; in Experiment II, photons, which would be in approximate equilibrium with any high energy electron component, would have created in a narrow lead plate at D electrons that would have recorded in the lower telescope. Neglecting any appreciable contribution to the counting rate by high energy protons, which cloud-chamber[2] work at similar altitudes has shown to be small in the same energy range, it has been assumed that the radiation producing our absorption curve consists predominantly of mesotrons. Range-energy relationships for ionization losses of mesotrons assumed to have mass 200 m_e make possible the calculation[3] of the number of mesotrons having energies sufficient to penetrate 10-, 20-, 30-, 40-, and 50-cm Pb. From the differences between values for these successive thicknesses a differential energy spectrum of the mesotrons has been obtained. This block spectrum is plotted in Fig. 4; the height of each block represents the number of counts (per min. per 100-Mev interval) produced by mesotrons traversing the telescope with energies in the energy range indicated by the base of the block.

On the basis of the McKinley spectrum at 37.2-cm Hg, calculations have been carried out to obtain the mesotron spectrum which would be expected at the elevation of Mt. Evans, 45.7-cm Hg, on the following assumptions: (a) the mesotrons with which we are concerned lose energy predominantly by ionization; (b) they have a rest mass of 200 m_e and a mean life at rest of 2.1 microseconds; (c) their latitude effect between McKinley and Mt. Evans is negligible; and (d) no additional mesotrons are produced between these two altitudes. A formula in which ionization loss and mesotron decay are combined gives the diffusion of mesotrons. According to these calculations the McKinley mesotron spectrum will give rise to a spectrum at the altitude of Mt. Evans, as shown by the curve B. (The points indicated by triangles were obtained from the midpoints of the three blocks in the right portion of the McKinley spectrum. The dashed curve B is obtained by using the dotted curve above drawn to fit the blocks of the McKinley spectrum.)

For comparison, there is also plotted in Fig. 4 the differential mesotron energy spectrum A from the experimental data obtained on Mt. Evans by Hall.[4] We have normalized his data to ours by using the ratio of mesotron intensity through 167 g/cm² Pb between Mt. Evans and sea level found by Greisen.[5]

[2] W. M. Powell, Phys. Rev. **69**, 385 (1946).

[3] We are indebted to Dr. John A. Wheeler for the use of energy-range curves calculated at Princeton.

[4] D. Hall, Phys. Rev. **66**, 325 (1944).

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

DISCUSSION OF SLOW MESOTRON INTENSITIES

The large discrepancy between the experimental curve *A* and the curve *B* predicted on the basis of the McKinley spectrum, strongly indicates that considerably more mesotrons of energy less than 400 Mev are found on Mt. Evans than could, according to our assumptions, have diffused to that point from higher altitudes. It seems difficult to account for this discrepancy except by the production of mesotrons in the atmosphere between the two elevations, 18,100 and 14,250 feet. The difference between curves *A* and *B* between 80 and 400 Mev represents a production of mesotrons totaling about 0.06 counts per minute in the McKinley telescope (or equivalent to 0.17 mesotrons per min. per unit solid angle per cm^2), which corresponds to 14 percent of the McKinley mesotron intensity through 10-cm Pb. This production must have taken place between McKinley and Mt. Evans altitudes in a layer of air of mass 115 g/cm^2. Furthermore, it is very difficult to imagine that the lower energy ranges of the McKinley mesotron spectrum itself could have been produced solely by the diffusion of mesotrons from near the top of the atmosphere; this large increase at low energies seems another direct indication of some secondary process. A remarkably large intensity of mesotrons at this same altitude and energy (200 Mev) has also been reported from airplane cloud-chamber investigations by Moore and Brode.[6]

Production of mesotrons has been previously investigated by several authors. On Mt. Evans, Tabin[7] and Rossi and Regener[8] found that production of penetrating particles by non-ionizing radiation in thicknesses up to 124 g/cm^2 Pb and 9 g/cm^2 paraffin was not greater than 1 percent of the Mt. Evans mesotron intensity through 10-cm Pb. However, a considerable production was reported above 25,000 feet by Schein and Wilson.[9] The results in our Experiments II and III on the production of mesotrons by ionizing and non-ionizing radiation in thicknesses up to 68 g/cm^2 Pb and 5 g/cm^2 paraffin at 18,100 feet have been presented. Although adverse weather conditions cut down the recording time and hence the accuracy of these experiments, no positive evidence for any production effect in matter was found, and it appears that any production in excess of three percent of the total mesotron intensity could not have escaped detection. The calculated production effect of 14 percent of the McKinley mesotron intensity, in the layer of air of 115 g/cm^2, seems larger than can be accounted for by the results of the experiments on Mt. McKinley with solid matter. Further experiments of higher precision should clearly demonstrate whether production of mesotrons in matter is frequent enough to account for the large number of slow mesotrons, or whether some other process may be involved. The decay of a neutral particle (such as that reported by Rochester[10]) into positive and negative mesotrons, for example, while escaping detection in experiments with small layers of Pb and paraffin, could in traversing a long path in air give rise to an appreciable number of slow mesotrons.

We wish to thank Bradford Washburn, Director of the Boston Museum of Natural History, for his excellent leadership and cooperation during the whole expedition. It is a special pleasure to acknowledge the fortitude and skill of Mr. H. T. Victoreen in the actual operation of the equipment on the mountain under extremely rigorous conditions. General Carl A. Spaatz kindly made arrangements with the Army Air Forces to drop the apparatus by parachute at Denali Pass, which greatly facilitated carrying out the experiments.

[6] D. C. Moore and R. B. Brode, Phys. Rev. **73**, 532 (1948).
[7] J. Tabin, Phys. Rev. **66**, 86 (1944).
[8] B. Rossi and V. Regener, Phys. Rev. **58**, 83 (1940).
[9] Marcel Schein and V. C. Wilson, Phys. Rev. **54**, 304 (1938).
[10] G. D. Rochester and C. C. Butler, Nature **160**, 854 (1947).