radiation will likewise be proportional to the atomic number.

## CONCLUSION

The present work indicates that the total intensity in the continuous radiation of x-rays at 1.1 kv to 2.0 kv, as measured and partially corrected, is proportional to the atomic number and to some power of the voltage higher than the second. The shape of the curve resembles that to be expected from a thin target.

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# The Mass of Cosmic-Ray Mesotrons*

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By cloud-chamber observations of the curvature of mesotrons in a magnetic field of 4750 gauss and the subsequent range of these same particles in a second cloud chamber containing fifteen lead plates each 0.67 cm in thickness, the mass of 43 cosmic-ray particles has been determined. 37 of these particles appear to give a set of observations that are consistent with a unique mass of $215\pm4$ times the mass of an electron. Of the 6 remaining observations 4 indicate a mass much too large (474, 538, 588, and 717) to be reasonably considered as statistical fluctuations in the observations of normal mesotrons. The remaining 2 observations (114 and 120) also appear to be inconsistent with the normal mass of the mesotron and the observed probable errors in individual measurements in this experiment.

A NUMBER of experimental studies of the mass of cosmic-ray mesotrons have been made. Some of the earlier data have been discussed by Wheeler and Ladenburg,[1] and by Hughes.[2] More recent studies have been reported by Fretter,[3] Lattes, Muirhead, Occhialini, and Powell,[4] LePrince-Ringuet and M. Lheritier,[5] and by Alichanian, Alichanow, and Weissenberg.[6] Since the work on which this report is based was completed, the detection and identification of mesotrons produced artificially by the 184-inch cyclotron has been accomplished by Lattes and Gardner.[7] The purpose of the work reported here was to add to the data on the mass of the mesotron and to try to improve the accuracy of the measurement.

## THE EXPERIMENTAL APPARATUS

The experimental arrangement is illustrated in Fig. 1. The upper cloud chamber, $CH_1$, was placed in a magnetic field of 4750 gauss. The chamber was 12 inches in diameter and 3 inches deep. $B$ represents a baffle system which consisted of two perforated brass sheets and a drilled plate 0.25 inch thick, which were separated by 0.25-inch spacers. Velvet was fastened to the front of the first perforated sheet to provide a black background for photography. The baffle was intended to smooth out irregularities in the expansion caused by uneven motion of the rubber diaphragm, $R$. An asymmetrical arrangement of two expansion ports, $E$, resulted in a detectable distortion of the tracks. This distortion was reduced but not eliminated by installing a symmetrical arrangement of three expansion ports (see the discussion of errors). The upper cloud chamber was filled with air and a 3:1 mixture of ethyl alcohol and water to a total pressure of 1.13 atmospheres in the expanded position. The chamber was not saturated with liquid but the amount of vapor was adjusted to keep the expansion ratio in the range of 14 percent to 16 percent. A clearing field of 100 volts between the metal back plate and an aquadag ring on the front glass was reduced to zero as soon as possible after the passage of the tripping particle through the Geiger counters, $C$. Illumination was provided by two GE FT 422 flash lamps each of which was excited by the discharge of a condenser of 160-$\mu$f capacity charged to 2000 volts. The illuminated region was 1 inch deep and the full height of the cloud chamber. The tracks were photographed on Ansco Ultra-Speed 35-mm film in a single frame camera using a Summar lens of focal length 5 cm at an aperture of $f$:9.

To reduce the effects of temperature variations a copper heat shield was built around the upper

* Assisted by the Joint Program of the ONR and the AEC.
** Now at Indiana University, Bloomington, Indiana.
[1] J. A. Wheeler and R. Ladenburg, Phys. Rev. **60**, 754 (1941).
[2] Donald J. Hughes, Phys. Rev. **69**, 371 (1946).
[3] William B. Fretter, Phys. Rev. **70**, 625 (1946).
[4] Lattes, Muirhead, Occhialini, and Powell, Nature **159**, 694 (1947).
[5] L. LePrince-Ringuet and M. Lheritier, J. de Phys. et Rad. **7**, 65 (1946).
[6] Alichanian, Alichanow, and Weissenberg, J. Phys. U.S.S.R. **11**, 97 (1947).
[7] C. M. G. Lattes and E. Gardner, Science **107**, 270 (1948).

cloud chamber and the conical hole in the core of the magnet through which the chamber was photographed. Copper tubing soldered to the heat shield carried water which was temperature controlled to ±0.25°C. A sheet of transite between the heat shield and the back pole face of the magnet and asbestos lining in the conical hole in the front core insulated the heat shield and the cloud chamber from the magnet. Windows, *W*, in the heat shield permitted illumination of the chamber and helped to form the light beam.

The original intention had been to use helium in the upper cloud chamber because of the small scattering to be expected. To obtain an estimate of the error in the curvature measurements because of the turbulence in the gas in the chamber, 48 no-field tracks in helium were studied. The coordinates of the track were measured in a traveling microscope and the radius of curvature of the best fitting circle was calculated by the method of least squares. The average curvature of these 48 tracks was 0.053 ±0.055 meter$^{-1}$. Since most of these particles would have much higher energy than the particles which were of interest in this experiment, it is seen that most of this spurious curvature is due to turbulence and very little of it is due to scattering. The residual, or no current, field was found to be less than one gauss, which is too small to explain any of the observed effect. For a particle of energy such that the radius of curvature of its trajectory in a magnetic field of 4750 gauss would be 1.5 meters—such a mesotron would stop near the middle of the lower cloud chamber—the probable error in radius of curvature resulting from turbulence would be 8 percent, while the probable error resulting from scattering would be 0.7 percent.

With air in the upper cloud chamber, 60 no-field tracks were measured in the same way. The average curvature was 0.03±0.04 meter$^{-1}$, giving a 6.25 percent probable error caused by turbulence for a track of 1.5 meters radius in a field of 4750 gauss. The scattering probable error in air for the same particle would be 2 percent. It is seen that by using air in the chamber instead of helium the decrease in the error caused by turbulence more than offsets the increase in the scattering error. The

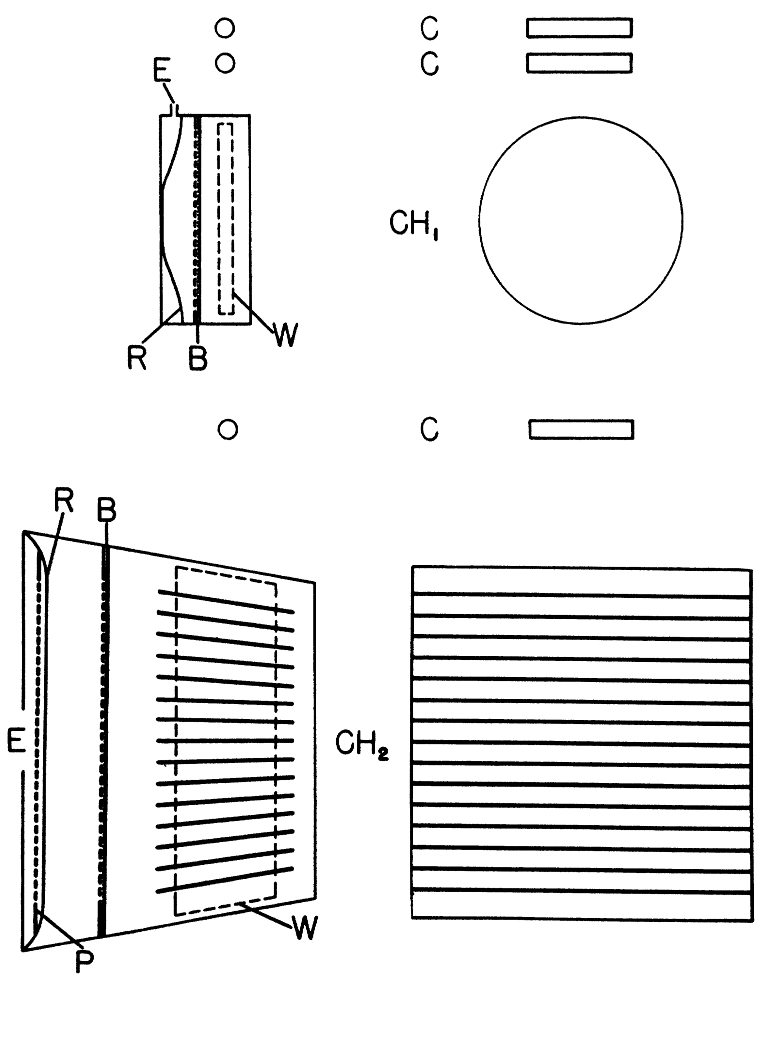


FIG. 1. Schematic arrangement of cloud chambers. $CH_1$ and $CH_2$, upper and lower cloud chambers. *E* exhaust port. *R* rubber diaphragm. *B* baffle plate. *W* window for illumination. *C* Geiger counter for control. The magnet in which cloud chamber $CH_1$ is placed is not shown, nor the heat shields for constant temperature control.

TABLE I. Mesotron mass measurements.

| Track no. | Sign | $C$ Curvature in unit field ×10⁶ (cm⁻¹ gauss⁻¹) | $R$ Range in lead (cm) | $m$ Mass in electron mass units | $\Delta m$ Probable error in mass |
|---|---|---|---|---|---|
| 4505 | − | 1.189 | 9.72 | 231 | 37 |
| 5051 | + | 1.804 | 6.13 | 189 | 22 |
| 5441 | + | 1.621 | 7.11 | 160 | 22 |
| 5706 | − | 2.208 | 2.93 | 202 | 24 |
| 5881 | − | 1.983 | 4.22 | 185 | 20 |
| 5986 | − | 1.563 | 7.83 | 161 | 21 |
| 5992 | − | 1.088 | 10.19 | 257 | 49 |
| 6062 | + | 0.988 | 4.98 | 538 | 84 |
| 6189 | − | 2.358 | 2.83 | 198 | 23 |
| 6459 | + | 1.334 | 7.13 | 252 | 37 |
| 6496 | − | 1.516 | 7.05 | 198 | 29 |
| 6576 | − | 2.015 | 4.33 | 180 | 27 |
| 6602 | − | 0.831 | 9.14 | 474 | 88 |
| 6659 | + | 1.128 | 10.36 | 235 | 44 |
| 6923 | + | 1.176 | 10.87 | 189 | 39 |
| 7049 | + | 1.816 | 4.41 | 211 | 20 |
| 7273 | + | 1.655 | 5.11 | 223 | 32 |
| 7275 | − | 0.816 | 7.06 | 588 | 110 |
| 7350 | − | 1.019 | 9.23 | 320 | 59 |
| 7371 | − | 1.457 | 6.28 | 225 | 31 |
| 7374 | − | 1.189 | 10.47 | 194 | 36 |
| 7433 | + | 1.316 | 7.38 | 255 | 41 |
| 7457 | − | 3.023 | 3.10 | 114 | 16 |
| 7614 | + | 1.631 | 4.26 | 269 | 34 |
| 7645 | − | 1.706 | 5.02 | 210 | 26 |
| 7647 | + | 1.402 | 7.27 | 216 | 36 |
| 7821 | + | 2.091 | 3.68 | 189 | 20 |
| 7847 | − | 1.252 | 6.97 | 282 | 45 |
| 7884 | − | 1.229 | 9.48 | 212 | 36 |
| 7900 | − | 1.651 | 5.85 | 194 | 28 |
| 7910 | − | 1.381 | 8.60 | 185 | 25 |
| 7919 | − | 2.060 | 2.96 | 225 | 27 |
| 7938 | + | 1.322 | 8.42 | 207 | 35 |
| 8093 | + | 1.402 | 8.44 | 182 | 27 |
| 8103 | − | 1.012 | 2.92 | 717 | 121 |
| 8145 | − | 1.485 | 5.84 | 240 | 34 |
| 8217 | − | 1.812 | 3.74 | 235 | 28 |
| 8275 | − | 1.258 | 4.98 | 360 | 50 |
| 8674 | − | 2.369 | 2.83 | 186 | 26 |
| 8818 | + | 1.968 | 2.99 | 240 | 28 |
| 9183 | − | 1.737 | 7.74 | 120 | 16 |

direction of the average spurious curvature is such as to make a positive particle appear heavier and a negative particle appear lighter.

The lower cloud chamber, $CH_2$, in Fig. 1, in which the range in lead for the particles was measured, was a truncated pyramid 20 inches square at the middle of the illuminated region and 17 inches deep. It contained 15 lead plates 0.270 inch thick and about 1 inch apart. The walls were 0.5 inch dural, the front window 0.5 inch heat-treated glass, and the side windows for illumination, 0.5 inch lucite.

The walls of the chamber and the lead plates all pointed at the camera 50 inches away so that the camera saw all of the space between plates. The chamber was filled with air at first, and later with equal parts of air and argon, and a 3:1 mixture of ethyl alcohol and water to total pressure of 1.35 atmospheres in the expanded position. The vapor content was kept just under saturation. The vertical clearing field between plates was 20 volts and was reduced to zero as soon as possible after the passage of the tripping particle through the Geiger counters. A region 6 inches deep and the full height of the chamber was illuminated by four GE FT 422 flash lamps, each excited by the discharge of a condenser of 256-μf capacity charged to 2000 volts. This chamber contained a baffle system similar to that in the upper cloud chamber and a drilled plate, $P$, to prevent the rubber diaphragm stopping the exhaust port and interfering with the flow of air from the back of the chamber on expansion.

The lower cloud chamber was photographed by a stereoscopic camera using two Apos lenses of focal length 105 mm at an aperture of $f$:8. Eastman Super XX air reconnaissance film, split to 1.75 inches from 7-inch rolls, was used. This camera also photographed a meter in series with the magnet to give a record of the magnetic field associated with each picture.

The cloud chambers were expanded upon passage of a charged particle through the triple coincidence Geiger counters, $C$. These counters defined a solid angle which filled the illuminated region of the upper cloud chamber and which was considerably more shallow than the illuminated region of the lower cloud chamber. At first 12 inches, and later 16 inches of lead were placed above the apparatus to select penetrating particle and to increase the number of particles stopping in the lower chamber.[8] This additional lead is enough to slow down the mesostrons at the peak of the energy spectrum so that they will stop near the middle of the lower chamber if they have mass 200 times the mass of an electron.

## OBSERVATIONS

The pictures from the upper cloud chamber projected full size, and the corresponding pictures from the lower chamber placed in a stereoscopic viewer, were examined together. Tracks of mesotrons of mass 200 $m_e$ that would be expected to stop in the lower chamber would have radii of curvature of 0.75 to 2.0 meter in the upper chamber. For each track that had a radius in or near this region, the pictures from the lower chamber were examined carefully for evidence that a particle had stopped. Also, whenever the pictures from the lower chamber indicated that a particle may have stopped in one of the lead plates, the picture from the upper chamber was examined carefully and measured. The distance of the track in the upper chamber from the middle of the chamber was measured in the projection for

[8] L. S. Germain, Phys. Rev. **75**, 1458 (A) (1949), reports measurements that indicate that the differential range spectrum of mesotrons increases only to a lead thickness of 9 inches and then decreases with further lead absorber; this indicates that the lead used in this experiment was more than desirable and increases the number of stopping particles by less than 10 percent.

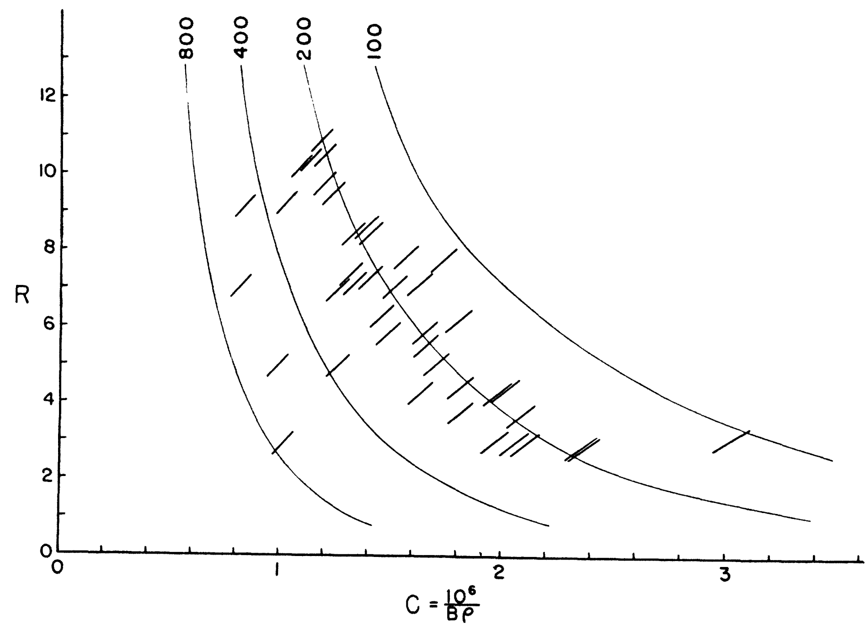


FIG. 2. Mesotron mass measurement. Each observation is plotted as a function of range, $R$, in centimeters of lead *vs.* curvature, $C$, in a unit magnetic field. The length of the lines representing individual observations is a measure of the probable error assigned to the measurement.

each of these particles. About 150 sets of pictures were examined carefully and measured. In about $\frac{2}{3}$ of these the particle had scattered out of the illuminated region before it had stopped, or it was not sufficiently clear that the particle had really stopped. The increase in ionization in the last two or three spaces traversed by the particle before it stops was helpful in distinguishing between particles that stop and those that are scattered out of the illumination. In five cases the presence of a lightly ionized track. indicating a decay electron, was strong evidence that a mesotron had stopped.[9] In one case, another track coming in from the side and of about the same age as the counter-controlled track could not be separated from the counter-controlled track and the data could not be used. This same case was the only one in which the data would be discarded because the measurement in the upper chamber was not acceptable, both ends of the track were separated into positive and negative columns by the clearing field, leaving a section in the middle which was too short to be accurately measured. A track ending in the first or second plate cannot be definitely identified as due to a penetrating particle. It is possible for an electron of 100 Mev to emerge from the bottom of the first plate unaccompanied by secondaries and then to stop in the second plate. For this reason, particles which stopped in one of the first two plates were not used unless, as happened in two cases, evidence for a decay electron indicated that the stopping particle actually was a mesotron.

For each particle that was of interest, the coordinates of the track in the picture from the upper cloud chamber were measured with a traveling microscope. These coordinates were plotted with considerable magnification in the direction perpendicular to the length of the track, and compared with the plots of circles to the same scale on celluloid to see how well the points fitted a circle. The radius of curvature of the best fitting circle was calculated for each track by the method of least squares. A correction to the curvature and the probable error in the measurement was assigned on the basis of the study of the 60 no-field tracks. The magnification of the camera system was measured by photographing a piece of millimeter cross section paper through a piece of 0.5-inch plate glass with the same geometry as was used in the experiment and measuring the film in the traveling microscope.

For each particle that was of interest one of the pair of pictures from the lower cloud chamber was examined in the traveling microscope. The projected angle on the film between the track and the normal to the plate was measured. The range in lead was taken to be the lead equivalent of the material between the chambers divided by the cosine of the angle in the top space of the lower cloud chamber, plus the sum over all the plates through which the particle passed of the thickness of the plate divided by the cosine of the angle in the space above the plate, plus half the thickness of the plate in which the particle stopped, divided by the cosine of the angle in the last space. The lead equivalent of the material between the chambers, the chamber walls, and the Geiger counter, as calculated from the equation for energy loss given by Rossi and Greissen[10] was 0.44 inch. This estimate of the range

[9] J. G. Retallack, Phys. Rev. **73**, 921 (1948).

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

does not take account of the backward or forward scattering of the mesotron in the lead plates of the lower cloud chamber. All of the particles enter the chamber very nearly in the vertical plane. If the scattering backwards or forwards, as can be seen with the stereoscopic views, is large, the particle will soon go out of the illumination. A very large scattering after entering the last plate, so that the particle travels a considerable distance before stopping, will lead to an appreciable underestimate of the true range and to a computed mass value that is heavier than its true value.

The magnetic field was measured with a flip coil of 130 turns $cm^2$ area and a ballistic galvanometer. The circuit was calibrated with a magnetic standard from the University of California Radiation Laboratory which was checked against a mutual inductance and a carefully calibrated ammeter. A careful check on the reading of the magnet current meter was maintained throughout the measurement. The field was uniform to 12-cm diameter, down 1 percent at 17-cm diameter, and down 2 percent at 20-cm diameter. The effective field was taken to be that uniform field that would have produced the same displacement at the center of the track and was calculated by graphical integration as a function of the track length and the distance of the track from the middle of the upper cloud chamber. In the vicinity of the operating point the magnetic induction varied linearly with current. The variation in the current was about 3 percent. The value of the induction associated with each picture was estimated from the photographic record of the magnet current.

The mass of each particle was then calculated with the aid of the curve relating range to momentum given by Wheeler and Ladenburg. These mass values are given in Table I, with the corresponding value of range ($R$), radius of curvature ($\rho$), and magnetic field ($B$). The curvature in unit field $\times 10^6$ ($C$) is calculated from the radius of curvature and the magnetic field.

## ERRORS

The largest errors in this experiment are due to the turbulence in the upper cloud chamber, distortion of the track by the front glass and camera system, and errors in the measurement of the track. The probable error in the curvature due to these causes is taken to be 0.04 $meter^{-1}$, as derived from the measurements on the 60 no-field tracks. For the average field used in this experiment of 4750 gauss, this error in curvature corresponds to a probable error in $C$, the curvature in unit field $\times 10^6$ of $\Delta C_T = 0.084$ $cm^{-1}$ $gauss^{-1}$.

The probable error due to scattering[11] was calculated on the assumption of a mass of 200 $m_e$. This error depends on the length of track, the magnetic field, and the velocity of the particles. For scattering in nitrogen the probable error in $C$ is $\Delta C_s = 0.02C$.

The error in magnification due to the plane in which the particle passes through the illuminated region introduces an error proportional to the curvature. From the depth of the illumination this error $\Delta C_m$ is estimated to be $0.01C$.

The probable error in measurement of the magnetic field is estimated as $\Delta C_B = 0.01C$.

The total error in the curvature, $C$, is compounded from these errors as $\Delta C = ((0.084)^2 + (0.025)^2 C^2)^{\frac{1}{2}}$. In the observations reported in Table I, $C$ varies from 1 to 3 so that $\Delta C$ varies from 0.09 to 0.10.

The probable error in range is estimated as one-fourth the plate thickness divided by the cosine of the angle of the track with the vertical as it enters the last plate, i.e., $\Delta R = 0.17$ cm/$\cos\theta$.

The probable error in the calculated mass arises from the errors in range, $\Delta R$, and in curvature $\Delta C$. In the plot of the observed data in Fig. 2. the curves of constant mass have been derived from the curves of Wheeler and Ladenburg.[1] The diagonal lines have their centers at the observed values of range and curvature. The length of the lines are such that the projections on the $R$ and $C$ coordinates are the extent of the probable errors $\pm\Delta R$ and $\pm\Delta C$.

## DISCUSSION

The results of the observations on 43 particles are shown in Fig. 2. The value of the mass corresponding to the curve that best fits this data can be determined by the least squares adjustment.[12] It can be seen, however, that the probable errors assigned to these observations are nearly constant in the range curvature coordinate system, and the measure of linear distance orthogonal to the curves of constant mass is closely proportional to the log of the mass. Taking all of the 43 observations and weighting each inversely as the square of ($\Delta m/m$), the value of $m$ corresponding to the mean of $\log m$ is found to be 217 in units of the electron's mass.

The ratio of the probable error based on external consistency to the probable error based on internal consistency[13] is 1.81. For 43 observations the probable deviation from unity of this ratio is 0.11. The chance for a deviation from unity 7.5 times the probable deviation is extremely small indicating that these observations are not consistent with the assumption of a unique mass.

If the four highest and the two lowest mass values are omitted, the remaining 37 values form a consistent set of observations. The ratio of the probable error based on external consistency to the probable

[11] H. A. Bethe, Phys. Rev. **70**, 821 (1946).

[12] Robert B. Brode, Phys. Rev. **75**, 904 (1949).

[13] R. T. Birge, Phys. Rev. **50**, 207 (1932).

error based on internal consistency differs from unity by 0.10. For 37 particles the calculated deviation from unity of this ratio is 0.12. The mean value of the mass of the mesotron in electron mass units deduced from this consistent set of 37 observations is $215 \pm 4$.

The existence of six observations that are not consistent with the other observations may indicate that the probable errors assigned to the individual observations are too small, or that the mass of the mesotron as observed at sea level is not unique. The existence of a small percentage of the $\pi$-mesotrons[14] in the normal, or $\mu$ mesotron spectrum would not be resolved in a series of observations with probable errors as large as indicated here.

The existence of mesotrons with lighter and heavier masses has been suggested by the observations of Hughes,[2] LePrince-Ringuet,[5] and Alichanian, Alichanow, and Weissenberg.[6] Adequate evidence for the existence of these particle will require the accumulation of more data. The chance of mistaking a normal mesotron for such a particle can be appreciably reduced by using thinner absorbing plates to reduce the error in range and by careful design and control of the cloud chamber to reduce turbulence.

[14] Lattes, Occhialini, and Powell, Nature **160**, 453, 486 (1947).

### ACKNOWLEDGMENTS

One of us (J.G.R.) takes this opportunity to acknowledge the assistance of a Westinghouse Fellowship in Physics. We are indebted to Professor R. T. Birge for his interest in the statistical interpretation of the data, and to Mr. R. R. Brown, who built most of the control circuits.

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# The Properties of Cosmic Radiation in the Lower Atmosphere*

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Experiments performed previously with apparatus carried to very high altitudes by free balloons have been conducted in the lower portion of the atmosphere. Two different instruments were operated in a B-29 airplane, and at Mt. Evans, Colorado. Absorption curves in lead, up to a thickness of 18 cm, were obtained at 14,260 feet, 25,000 feet, and 30,000 feet. Intensity *vs.* altitude curves for the lower regions of the atmosphere may now be combined with those for very high altitudes without an arbitrary normalization. A direct comparison has been made between the present measurements and those of others regarding the relative change of intensity between sea level and Mt. Evans, and the absorption in lead at Mt. Evans. Factors for the conversion of all of the data to absolute intensities have been determined utilizing a $\gamma$-ray howitzer method for measuring the effective length of a G-M counter. Satisfactory agreement is noted between values of the absolute intensity previously measured by others at sea level and at Mt. Evans, and those reported herewith. The absolute intensity of cosmic-ray particles near the "top of the atmosphere" at geomagnetic latitude 52°N is given as $10.1 \pm 0.20$ particles/min./cm$^2$/unit solid angle. Consideration is given to the considerable error which may be introduced in the comparison of measurements of the "total" intensity at very high altitudes obtained with different G-M counters.

## I. INTRODUCTION

THE results of a series of investigations of the cosmic radiation in the upper regions of the atmosphere have been described recently.[1] Owing to a combination of the smaller intensity present at lower altitudes, and the relative briefness of the time interval during which free-balloon flights remain in regions of high atmospheric pressure (a consequence of the exponential variation of pressure as a function of altitude, and accentuated by the particular ballooning techniques employed here), data obtained at altitudes corresponding to pressures exceeding approximately 200 mm of Hg were not in general regarded as statistically significant.

The purpose of the present series of experiments was threefold:

(1) To obtain data at lower altitudes with the same apparatus utilized in the free-balloon ascents, thereby providing complete intensity *vs.* altitude curves, as well as cosmic-ray absorption curves for lead from sea level to the "top of the atmosphere;"
(2) To permit comparison of certain of the numerous measurements at various low altitudes (4350 meters—sea level) previously reported by others with those which would be yielded by the aforementioned apparatus. Comparison at more than one point furnishes a less arbitrary normalization than has usually been assumed.[2]
(3) To provide experimental evidence regarding the validity of comparison of data obtained with different geometrical arrangements, and specifically, to furnish at several altitudes a direct and precise standardization between two particular counter trains of different dimensions utilized in the balloon flight program.

* Assisted by the Joint Program of the ONR and AEC. Field trips were sponsored by the National Geographic Society.

[1] M. A. Pomerantz, Phys. Rev. **75**, 69 (1949).

[2] This matter has been discussed in reference 1.