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The Average Ionization and Energy Loss of Cosmic-Ray Mesotrons in Air

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The average specific ionization of cosmic-ray mesotrons has been determined at sea level and at 100 feet underground from drop counts along diffuse cloud-chamber tracks. The cloud chamber was operated in such a way that the efficiency of condensation on ions was known. The average specific ionization, excluding energy transfers greater than 800 ev, is essentially 50 ion pairs per cm of air at N.T.P. for both locations. Since a 15 percent increase is expected for the measurements underground, it is suggested that the high energy cosmic rays may be protons. If all energy transfers less than 10^4 ev are included, the average energy loss is 1.35×10^6 ev per g/cm^2 of air, in reasonable agreement with the theory. The observed cross sections for energy transfers between 800 and 3200 ev agree with the Rutherford formula when the electron binding is taken into account.

THE energy loss of ionizing cosmic-ray particles in gases is determined indirectly from ionization measurements. For mesotrons the energy loss in air from nuclear (radiative) collisions is negligible for energies less than 10^{11} ev;[1] since more than 98 percent of the mesotrons at sea level have energies[2] less than 10^{11} ev, radiation loss can be neglected. The total number of ions produced by *low energy* ionizing rays of known energy has been measured by several different methods.[3] The average energy loss per ion pair is independent of the energy of the primary particle and has a value of 32 ev per ion pair for air. Since the entire energy of even a cosmic ray is ultimately dissipated in low energy transfers, it is reasonable to assume that the factor, 32 ev per ion pair, can be used in converting from ionization to energy loss in the case of cosmic rays.

Several measurements, both of the primary ionization and of the "total" ionization, have been made in a variety of gases and by several different methods.[4,5] The determinations of primary ionization, which have been made from cloud-chamber photographs and from counter efficiency measurements,[4] are relatively accordant.[6] But the measurements of total or probable ionization give discordant results.[4,5] The values obtained by combining ionization chamber and counter measurements (i.e., division of the total number of ions formed per sec. per cm^3 by the number of particles traversing a unit volume per sec.) are subject not only to the uncertainties in the results of each of the two types of experiments, but also to the uncertainty in establishing the applicability of the counter data to the ionization chamber environment. The pulse-ionization chamber method is subject either to

[1] H. J. Bhabha, Proc. Roy. Soc. **A164**, 257 (1938).
[2] P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937).
[3] H. Eisl, Ann. d. Physik **3**, 379 (1929). C. E. Nielsen, Ph.D. Thesis, University of California (1941).
[4] T. H. Johnson, Rev. Mod. Phys. **10**, 193 (1938).
[5] R. B. Brode, Rev. Mod. Phys. **11**, 222 (1939).
[6] W. E. Hazen, Phys. Rev. **63**, 107 (1943).

many experimental difficulties or to uncertainties in the interpretation of the data and, as a result, only one really quantitative experiment has thus far been performed.[7]

Only a high pressure ionization chamber measures a value for the ionization approximating the total ionization. In low pressure ionization chambers many of the ions are undetected because they occur along the tracks of secondaries of range greater than the chamber size; in cloud chambers a relatively short total track length is observed and the infrequent high energy transfers are not likely to be observed. With the cloud chamber, therefore, it is possible to obtain values for the ionization that include collisions in which the cosmic ray loses as much as several thousand electron volts with a reasonable number of pictures, but a determination of the total ionization might require many thousand. In the present experiment the average ionization of mesotrons has been determined at sea level and under 100 feet of rock. From these figures we can obtain a value for the average energy loss of mesotrons in air that includes all collisions in which 10^4 ev or less are lost by the mesotron in a single encounter.

The theory of ionization and energy loss of high speed charged particles leads to the prediction that both quantities increase with the energy of the high speed particle when its kinetic energy is greater than three times its mass energy. Direct measurement of the increase in primary ionization with energy was first attempted by Kunze,[8] but with negative results. His results have since been explained by the fact that he was observing mesotrons rather than high energy electrons. A study of the ionization by cosmic-ray electrons by Corson and Brode[9] indicates a rise in ionization with energy but their results involve a large uncertainty concerning the efficiency of condensation on ions. Sen Gupta[10] performed a similar experiment with a technique stated to be similar to that of Corson and Brode and with a magnetic field strong enough to deflect some of the mesotrons and protons. There was an indication of an increase in ionization with energy for the electrons, but only a slight increase for the mesotrons. Either the drop images were poorly resolved or the condensation efficiency was low since the observed average ionization for mesotrons was only 40 ion pairs per cm in air at N.T.P.

Experiments on the energy loss of mesotrons in metal plates[11] also indicate an increase with energy, but the increase was not significantly greater than the experimental uncertainty. A previous experiment by the author[6] showed that the average primary ionization by mesotrons was no higher than the minimum ionization by electrons, whereas calculations predicted a value at least ten percent higher.

In the present experiment we have a comparison of the average ionization by two groups of mesotrons, one with a much higher average energy than the other, and we should expect to find an increase in average ionization for the group with the higher average energy.

EXPERIMENTAL METHOD

The first pictures were taken in the downgrade fresh-air duct of the Broadway Low Level Tunnel in Oakland, California, at a depth of 100 feet (a few pictures were obtained at 400 feet). The lower half of the 30 by 30 cm cylindrical chamber contained four lead plates, but this portion of the cloud chamber was not photographed in all of the expansions. The upper portion of the chamber contained an electrode system that supplied a uniform horizontal electric field normal to the chamber axis—thus, by delaying the expansion an appropriate length of time, the cosmic-ray "track" becomes a pair of separated diffuse columns of ions, one positive and the other negative.

When the expansion is completed, some of the ions act as nuclei for drop formation. Studies of the condensation efficiency of the ions,[3,12] indicate that, with ethanol-water mixtures in the neighborhood of the ratio 3:1, over 95 percent of the plus ions form drops when the observed ratio of minus to plus drops is 1:10 and is essentially 100 percent when the ratio is greater than 1:5.

[7] W. C. Dunlap, Ph.D. Thesis, University of California (1942).
[8] P. Kunze, Zeits. f. Physik **83**, 1 (1933).
[9] D. R. Corson and R. B. Brode, Phys. Rev. **53**, 773 (1938).
[10] R. L. Sen Gupta, Nature **146**, 65 (1940).
[11] J. G. Wilson, Proc. Roy. Soc. **A172**, 517 (1939).
[12] G. D. Bagley, Phys. Rev. **56**, 851A (1939).

Since the alcohol diffuses through the rubber diaphragm and must be replenished periodically, the mixture usually is not in the ratio 3:1. Nielsen also made a few measurements with ethanol-water mixtures containing 40 percent and 87 percent ethanol. These measurements show that the condensation efficiency is certainly very close to 100 percent in the vapor from the above mixtures when the observed ratio of minus to plus drops is greater than 1:2. In the present experiment the ratio of drops in the minus and plus ion columns was used as the criterion for condensation efficiency on plus ions.

Counter control was obtained from four counter tubes in double coincidence placed above the chamber; the counting rate was one in three minutes at a depth of 100 feet. A seven-centimeter thickness of lead was placed above the counters in order to distinguish between the soft and the hard component; photographs with more than one track were discarded since, although nearly all such events consist of a mesotron accompanied by an electron, it is usually impossible to identify the mesotron in such cases. Ordinarily it is necessary to place lead below the counters in order to detect cases in which a divergent knock-on electron from the upper lead plate trips the counters, but in this experiment the cloud chamber was so large that the mesotron also would be observed.

Since the chamber was expanded by a relay, which introduced a delay in the expansion, and the expansion itself was relatively slow, no additional time delay was necessary in order to produce sufficiently diffuse tracks (2.5-mm diameter). The clearing field was maintained at 20 volts/cm until shorted by the coincidence-circuit relay. The delay inherent in the clearing-field relay permitted a separation of the plus and minus ions by six or seven millimeters before the clearing field fell to zero. Figure 1 shows one of the tracks as an example.

Illumination was provided by two argon flash tubes, each of which was mounted slightly outside the focal point of a set of condensing lenses. The beams of light were directed forward at an angle such that the light reaching the camera was scattered by the drops through an angle of $\sim 55°$. The flash tubes used in this experiment are the most satisfactory light source ever employed in

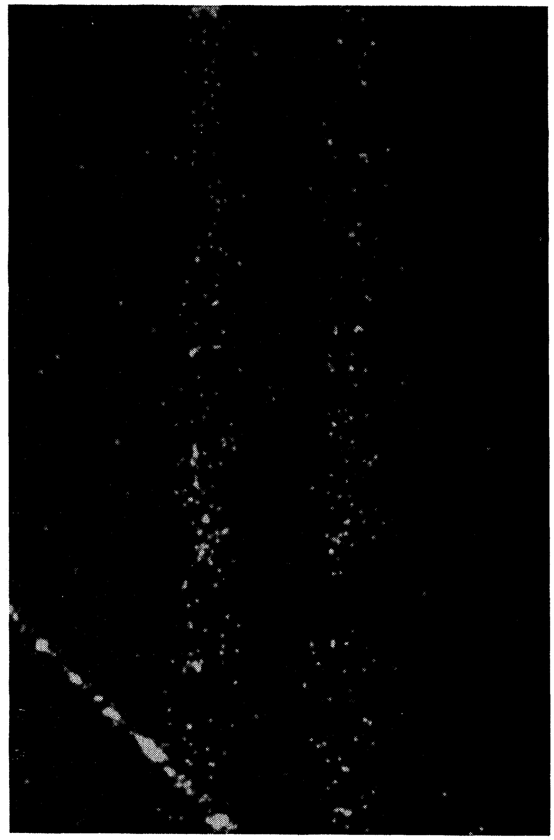


FIG. 1. An enlarged section of one of the mesotron tracks. The ions not only have diffused but also have separated into columns of plus and minus ions before the drops formed. The denser column of drops formed on the plus ions. The actual length of the portion of the original track here reproduced was 4 cm.

this laboratory;[13] the lumen-second output during the exposure is at least as great as that for any other type of source, and the average life is roughly 1000 flashes. With exposures at f:18 and a magnification of 0.157, the depth of focus was four centimeters for a circle of confusion less than 0.002-cm radius (the minimum circle of confusion was 0.001 cm).

In the case of the experiments at sea level, the lead plates were removed and the 30 by 30 cm cylinder was replaced by a 30 by 45 cm cylinder. The transverse clearing field was thus extended to include a 30 by 30 cm cylindrical region; the rear third of the glass cylinder was left free for the

[13] The flash tubes and accompanying circuits were developed by Dr. Eugene Gardner in connection with another experiment.

entrance of the light beam. Single counters were placed above and below the chamber with the lead above the upper counter.

Johnson[4] mentions three objections to the cloud-chamber method of determining specific ionization along diffuse tracks: (a) poor resolution in the clusters, (b) unobserved ionization at a distance from a track, resulting from x-ray excitation, and (c) recombination of ions in the absence of any electric field. (a) In the present experiment, all clusters that were not well resolved in the plus column were counted in the less dense minus column, and the result was multiplied by the ratio of plus to minus drops in the neighboring lengths of track. The energy, and thus the ionization, in branches with appreciable range, were obtained from a measurement of the range (there was no magnetic field which would deflect the branch electrons). (b) The calculated distance for absorption of one-half of the oxygen x-rays is only 3 mm according to Nielsen[3] and observations, both by Nielsen and by the author, have never given evidence for ionization clusters noticeably separated from a diffuse track. (c) In the present experiment there was an electric field to separate the ions.

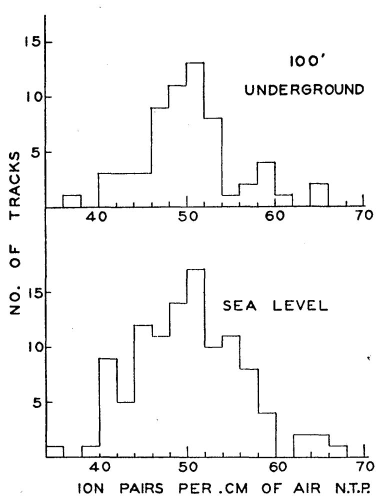


FIG. 2. Block diagrams showing the frequency distributions in the data for the specific ionization of cosmic-ray mesotrons. The mean value is 50 for the upper curve and 51 for the lower curve. The abscissae can be changed to electron volts by multiplying by the factor 32 ev/ion pair.

The source of the greatest uncertainty in the cloud-chamber method has usually been the uncertainty in condensation efficiency. This is probably the case in the present work.

EXPERIMENTAL RESULTS

The drop counts were made on the negatives themselves with a comparator microscope. The number of drops in the positive column averaged $\sim$700 per track for the Broadway Tunnel photographs and $\sim$1000 per track for the sea level photographs. Clusters of drops numbering 25 or more (the actual clusters contained 40 or more drops but the average ionization was 15 in the length of track occupied by a cluster) were considered apart from the general drop count. It was found that statistical variations from one track to the next were greatly reduced when larger clusters were excluded, but on the other hand the criterion for exclusion was applied so infrequently that no appreciable error resulted from cases where the cluster size was $\simeq$25.

In order to reduce the data to number of drops per cm at N.T.P., factors involving temperature, pressure, and magnification were considered. A fiducial magnification was established photographically at a distance approximately the same as the original track distances; the distance and inclination angle (small for the Broadway Tunnel tracks, negligibly small for the sea level tracks) of individual tracks were determined by reprojection, and the magnification was calculated for each track. Block diagrams of the distributions for both sets of data are given in Fig. 2.

The average ionization is 51 per cm at sea level, and it is 50 per cm 100 feet underground. The statistical uncertainty in the ionization of an individual track is determined essentially by the number of primary ionization events, which is 20 per cm in air or 40 percent of the ionization observed in the present experiment. The probable statistical deviation in the ionization of an individual track is thus: $0.67\times 50/(0.4\times 1000)^{\frac{1}{2}}=1.7$ ions per cm at sea level and 2.0 ions per cm 100 feet underground. Both distribution curves are many times broader than would be expected on the assumptions that the main uncertainty is statistical variation in the ionization and that each track is a measurement of the same quantity. Without doubt neither assumption is justified.

The energy loss in electron volts represented by a given number of ion pairs is obtained by multiplying the number of ion pairs by 32. As noted above, clusters of 25 or more drops were recorded as separate events, i.e., each collision in which the mesotron lost 800 or more ev was listed. In the sea level drop counts, the total

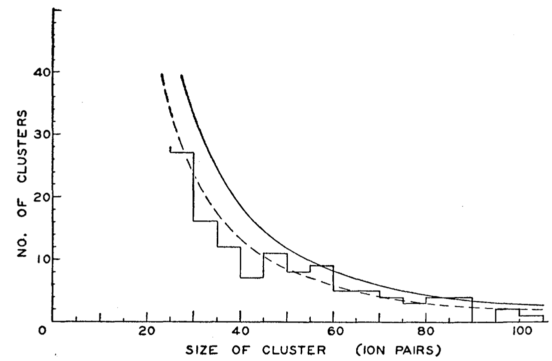


FIG. 3. Frequency distribution for clusters of ions in the tracks of cosmic-ray mesotrons. Each cluster arises from a collision in which a mesotron transfers to an electron an energy (in electron volts) of 32 times the cluster size. The solid curve is given by the Rutherford formula on the basis of free electrons; the dashed curve, by the same formula for bound *K* electrons.

number of ion pairs occurring in clusters of 25 to 310 was 7620, whereas the total number of ion pairs excluding clusters larger than 25 was 96,000. Thus the average ionization including energy transfers up to 10^4 ev (clusters up to 310) is 51 increased by 7620/96,000 or 54 ion pairs per cm in air at N.T.P. The corresponding energy loss is 1700 ev/cm or 1.35×10^6 ev per g/cm^2 of air. In Fig. 3 is given a frequency distribution for the energy losses greater than 800 ev.

INTERPRETATION OF RESULTS

The theoretical value for the minimum energy loss[14] is 1.28×10^6 ev per g/cm^2 in air for energy transfers less than 10^4 ev. Since the average energy loss is certainly somewhat higher than the minimum energy loss, we can consider the agreement with the measured value of 1.35×10^6 as satisfactory.

The expected average ionization for a group of mesotrons is

$$\int I(E)\cdot f(E)\cdot dE / \int f(E)\cdot dE,$$

where $I(E)$ is the specific ionization for energy E, and $f(E)$ is the relative number of mesotrons with energy E to $E+dE$. Since $f(E)$ has actually been determined as $f(H\rho)$, it is more convenient to perform the numerical integrations in terms of $H\rho$ (all values of $H\rho$ will be given in gauss-cm). The spectral distribution $f(H\rho)$ obtained by Blackett[2] extends down to $H\rho=1.7\times10^6$ without corrections. Three lower points on the curve were obtained from: (1) Blackett's data for the number of particles in the range of $H\rho$ from 7×10^5 to 1.7×10^6, multiplied by the correction factor 3.28 to allow for the exclusion of particles by the magnetic field;[2] (2) Greisen's figure[15] of 0.08 for the fractional number of mesotrons in the $H\rho$ range 1.7×10^5 to 8.3×10^5; and (3) the isolated point given by Williams[16] at $H\rho=1.2\times10^5$. For values of $H\rho$ greater than 10^8, the spectrum is not known from direct measurements, but absorption measurements and other types of evidence lead to the assumption of a $1/E^3$ distribution. Fortunately, the calculated average ionization does not depend critically on the values of $f(H\rho)$ at low and high values of $H\rho$.

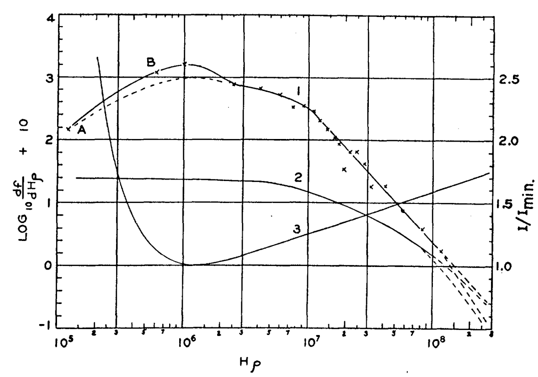


FIG. 4. Curves used in the integrations to obtain the expected average specific ionization of mesotrons. Curve *1* is the energy spectrum at sea level according to Blackett (points *A* and *B* are from data of Williams and Greisen, respectively). Curve *2* is the energy spectrum 100 feet underground, under the assumption that all of the particles lost 10^{10} ev in traversing the rock. On the ordinate scale for curves *1* and *2* (left), df is the relative number of particles in the $H\rho$ range $H\rho$ to $H\rho-dH\rho$. The dotted portions of curves *1* and *2* represent possible variations in the curves that arise from uncertainties in the measurements. Curve *3* is the ionization curve (scale of ordinates at the right).

Figure 4 shows the curves used in the numerical integrations. The curve for the spectrum 100 feet underground was obtained from the sea

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

[15] K. Greisen, Phys. Rev. **63**, 323 (1943).

[16] E. J. Williams, Proc. Roy. Soc. **A172**, 206 (1939).

level spectrum by assuming that all of the rays lost 10^{10} ev of energy in penetrating to the tunnel. There are two reasons for not considering the variation in energy loss with energy in determining the underground spectrum: The results are not appreciably altered, and the present experiment indicates no variation with energy. The results of the integrations are $I_0 = 1.18 \cdot I_{\min}$ (at sea level) and $I_{100} = 1.42 \cdot I_{\min}$ (at the tunnel). When variations that are believed possible are made at the lower and at the upper end of the spectra, the results are changed by two percent or less. Thus we are led to expect an increase of at least 15 percent in the average ionization when 100 feet of rock filter is added, whereas the experimental values for the average ionization are essentially identical. The frequency distributions (Fig. 2) are broader than one would expect from statistical fluctuations alone, but it seems highly unlikely that any experimental errors could mask a 15 percent difference in the means of the two distributions.

There are several possible phenomenological explanations, among which are: (1) the ionization does not increase with energy more than one-fourth as rapidly as the predicted increase; (2) the polarization effect takes place at energies lower by a factor of 50 than Fermi calculates;[17] or (3) most of the particles with $H\rho > 10^7$ are protons. The first possibility is not very likely since the increase in ionization is predicted on the basis of supposedly well-established precepts, and since available experimental results, although subject to large uncertainties, agree with the predicted rise. The second is also unlikely even though the theoretical calculations are admittedly rough. The third is not generally accepted, but other experimental evidence is not overwhelmingly against such a possibility; if true, some 30 percent of the hard component might consist at sea level of protons.

The frequency distribution for clusters and delta-rays of energy greater than 800 ev in the sea level tracks is given in Fig. 3. The total number of such collisions was 135 in a total track length of 1930 cm. The Rutherford formula applies to the types of collisions included in this study as far as considerations of spin, relativity, collision time, etc., are concerned,[14] but the assumption of free electrons is not justified for the two K electrons of oxygen or nitrogen in the lower energy collisions. However, the correct collision cross section is somewhere between that obtained by assuming all the electrons as free and that obtained by assuming the K electrons cannot be removed.

The Rutherford formula (for free electrons) with the constants evaluated is

$$N(E)dE = 98dE/E^2 \text{ cm}^{-1} \text{ ev}^{-1},$$

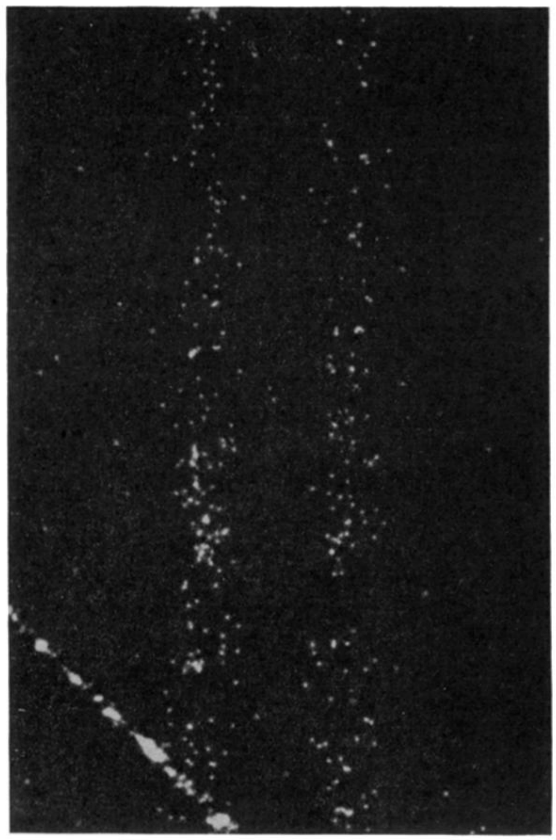
where $N(E)$ is the number of collisions in which energy E to $E+dE$ is lost by the mesotron per cm of air at N.T.P. For completely bound K electrons the factor 98 would be reduced to 71. The theoretical curve is a fairly satisfactory representation of the data when the K electrons are considered free for the higher energies and bound for the lower energies. Several groups[18] have measured the frequency of occurrence of collisions with much higher energy transfers (more than 10,000 ev). Hornbeck and Howell found reasonable agreement with theoretical calculations for the case of electrons. Seren has shown that the Rutherford formula agrees with experiment for the frequency of mesotron collisions resulting in energy transfers greater than 13,000 ev.

In general, there seems to be reasonable agreement between theory and experiment for the ionization by high speed particles, except for the comparison of the average specific ionization by filtered (100 feet of rock) and unfiltered penetrating rays.

The author is greatly indebted to Mr. F. I. Doane of the State Highway Department for permission to work in the Broadway Low Level Tunnel and for his general cooperation.

[17] E. Fermi, Phys. Rev. **57**, 485 (1940).

[18] G. Hornbeck and I. Howell, Proc. Am. Phil. Soc. **84**, 33 (1941); L. Seren, Phys. Rev. **62**, 204 (1942).



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