Ionization of High Energy Cosmic-Ray Electrons

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(Received August 4, 1947)

The ionization produced by high energy cosmic-ray electrons has been measured in a cloud chamber in order to determine whether the probable ionization produced by a high velocity particle continues to rise logarithmically with the energy, or whether it takes on a constant value as has been predicted theoretically. A lateral clearing field was arranged so that the ionization could be measured in the upper half of the cloud chamber; lead plates were placed in the lower half so that the electron would produce a shower from which its energy could be estimated. The ionization produced by electrons was measured and compared to the minimum ionization as determined from the average ionization produced by mesotrons. According to the theoretical formula of Halpern and Hall, the maximum ionization should be 1.4 $I_{\min}$. In most of the pictures taken the ionization was consistent with this value. There were several pictures, however, where the ionization was extremely high. These may either indicate that the theoretical formula is invalid, or that they may result from the coincidence of two or more particles. Such an event does not seem unlikely when the production of pairs is considered. When a high energy gamma-ray produces an electron-positron pair, the probability that the two particles come off in practically the same direction is very high; in the cloud chamber they would produce one track with doubly dense ionization.

1. INTRODUCTION

FOR low energies the ionization by a charged particle increases as its energy decreases because the particle spends a longer time in the vicinity of each molecule of the gas being traversed. On the other hand, when the velocity of the particle approaches that of light, relativistic effects must be taken into account; the field of the particle becomes extended in the direction perpendicular to the direction of motion, and is thus felt by more molecules. This results in an ionization that rises logarithmically with the energy. The usual expression[1] for the energy loss by a particle traversing a medium is given by:

$$K_\eta(E) = (2C\mu_e/\beta^2) \times\{\log[2\mu_e\beta^2\eta/(1-\beta^2)I^2(Z)]-\beta^2\}. \quad (1)$$

$K_\eta(E)$ is the energy loss per g/cm^2 produced by collisions in which the energy transferred is smaller than η, $I(Z)$ is the average ionization potential of an atom of atomic number Z, and C is 0.15 Z/A. The specific ionization differs from the rate of energy loss by an essentially constant factor, and hence we need make no distinction in the present instance where only relative values of specific ionization will be considered. For low energies the $1/\beta^2$ factor outside the parenthesis is important, but as β approaches unity the logarithmic term predominates.

Fermi[2,3] has calculated that the field of the oncoming particle polarizes the medium in such a way that some of the molecules that would be ionized according to the ordinary formula are shielded from the exciting field. This results in a much lower ionization for high energy particles. The most recent calculation of this reduction in energy loss was made by Halpern and Hall.[4] For very high energies the quantity which they suggest should be subtracted from Eq. (1) is:

$$2C\mu_e\{\log[ne^2/\pi m\nu^2(1-\beta^2)]-1\}, \quad (2)$$

where ν is the geometric mean of the atomic frequencies or 13.5 Z ev $=3.5\ Z\times10^{15}$ sec.$^{-1}$. The subtraction of this term results in the prediction that the collision loss will be constant above a certain energy, when only energy transfers up to $\eta<750$ ev are considered, and that the collision loss depends only on the electron density, n, of the medium being traversed. Figure 1 shows a plot of the ionization equation for electrons traversing helium. No collisions in which the energy transferred is greater than 750 ev are considered. The horizontal curve is the one predicted by Halpern and Hall. The density effect should set in at about 90 Mev and the maximum ionization should be 1.4 $I_{\min}$.

[1] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).
[2] E. Fermi, Phys. Rev. **56**, 1242 (1939).
[3] E. Fermi, Phys. Rev. **57**, 485 (1940).
[4] O. Halpern and H. Hall, Phys. Rev. **57**, 4596 (1940).

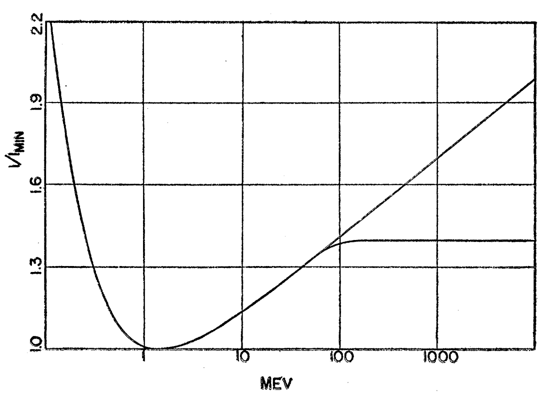


FIG. 1. The ionization curve for electrons traversing helium at normal temperature and pressure. Only energy transfers up to 750 ev are included. The horizontal curve, branching off near 100 Mev, is the one predicted by Halpern and Hall.

A rise in the ionization for energies just above that corresponding to the minimum ionization has been detected.[5,6] It seemed desirable to measure the ionization produced by the very high energy electrons contained in cosmic rays, because their energy can be estimated from the size and character of the showers they produce in passing through lead. The purpose of this experiment, then, was to measure the ionization by high energy electrons and to determine whether the ionization becomes constant or whether it increases with the energy.

2. APPARATUS AND EXPERIMENTAL PROCEDURE

A cylindrical cloud chamber having a diameter of 30 cm and a depth of 30 cm was arranged to observe both the ionization and the energy of the electrons. The ionization was measured in the upper half of the chamber and the energy in the lower. Five electrodes, extending from one end to the other, lined the upper half of the chamber and supplied a lateral clearing field (Fig. 2). Potentials of −200, −100, 0, 100, and 200 volts were applied to the electrodes. The cosmic-ray track was thus separated into a positive and a negative ion column, the separation being about 2 cm. Bagley[7] and Nielsen[8] have studied the condensation efficiency for the vapor mixture of three parts ethanol to one of water. Nielsen has shown that if the negative ion column is at least one-fifth as dense as the positive one, then drops are formed on all the ions in the positive column. This criterion for 100 percent condensation efficiency was used, and the ionization was measured by counting the drops in the positive column with a traveling microscope. Clusters corresponding to energy transfers greater than 750 ev, i.e., those containing more than 25 drops, were omitted. Those tracks that exhibited particularly high ionization were examined stereoscopically, and some of them proved to be due to two particles traveling through the cloud chamber. The remaining highly ionizing particles will be discussed in a later paragraph.

The lower half of the cloud chamber contained lead plates in which showers were produced by the incident electrons. In the first part of the experiment there were three one-quarter-inch lead plates; these were later replaced by two one-half-inch plates. The use of lead plates in this manner allows one to observe the shower at various stages in its development. A set of shower curves, in which the average number of particles is plotted as a function of the depth in shower units for various values of the energy of the initiating particle, was used to estimate the energy of the electron. These curves were plotted from Eq. (2.104) of Rossi and Greisen.[1]

The chamber was illuminated by two argon flash tubes. These were made from 12-mm Pyrex tubing with nickel electrodes sealed in the ends, the electrodes being separated by about 40 cm. The tubes were filled with 5 cm of argon and 0.1 cm of hydrogen. These were placed on either side of the chamber near the back in such a way that the light beams crossed in the center and passed out through the sides just behind the front glass. The resulting illumination was so intense that the cameras had to be stopped down to f:12.5 in order to make the drop images so small that their overlapping became unimportant.

Geiger counters in triple coincidence were arranged one above the chamber and two below. The two lower counters were placed in a vertical plane when the tracks of mesotrons were photographed and in the horizontal plane when those of electrons were selected, for a mesotron would

[5] D. R. Corson and R. B. Brode, Phys. Rev. 53, 773 (1938).
[6] W. E. Hazen, Phys. Rev. 67, 269 (1945).
[7] G. D. Bagley, Phys. Rev. 56, 851(A) (1939).
[8] C. E. Nielsen, Ph.D. Thesis (University of California, Berkeley, 1941).

go straight through the chamber whereas the shower produced by the electron would spread laterally and trip the counters in the horizontal plane. The expansion was delayed for a few hundredths of a second to give the tracks time to diffuse before the vapor was condensed on the ions.

The energy distribution of mesotrons at sea level is such that the ionization distribution resulting therefrom is narrow, and a small number of observations suffice to establish a reasonably accurate value for the mean. The minimum ionization is the same for both electrons and mesotrons, and since the average mesotron ionization is 1.12 times the minimum ionization,[6] the minimum ionization can be determined from the study of a few mesotron tracks. The average mesotron ionization was determined from thirty-four tracks, and the minimum ionization calculated from the average. The ionization caused by each shower-producing particle was then compared to the minimum ionization.

Since the pictures were taken under various conditions, i.e., different pressures and temperatures, the vapor pressure of the ethanol and water mixture was not constant. The ionization in the vapor was then different for each set of circumstances. A correction for this effect was made assuming that the ionization in each component of the gas is proportional to its atomic number Z and to its partial pressure. The total or observed ionization multiplied by the total gas pressure may be written as a function of the partial pressures of the component atoms:

$$IP = P_{\text{gas}}I_{\text{gas}} + I_{\text{H}}(2P_1+6P_2) + I_{\text{O}}(P_1+P_2)+2I_{\text{C}}P_2,$$

P_1 is the partial pressure of the water vapor and P_2 that of the alcohol vapor. If helium is the gas, I_{H} becomes $\frac{1}{2}I_{\text{He}}$, I_{O} becomes $4I_{\text{He}}$, and I_{C} becomes $3I_{\text{He}}$. The equation then reduces to:

$$IP = I_{\text{He}}(P_{\text{He}}+5P_1+13P_2).$$

The ionization in helium was found by this method, using the partial pressures of alcohol and water, as given by Gautier and Ruark.[9] The results were then reduced to normal temperature and pressure.

The experiment was begun with air as a gas in the chamber, but it soon became apparent that the ionization by high energy electrons in air at atmospheric pressure is too dense to be easily measured with the magnification of the present experiment. The chamber was then filled with about one and two-thirds atmospheres of helium; the remainder of the pictures were taken under these circumstances.

3. RESULTS

In helium the density effect should set in at an energy not greater than 100 Mev, and the maximum ionization should be 1.4 I_{min}. The effect should be apparent in the ionization caused by particles that later produce showers having more than four or five particles at the maximum. Only about ten percent of the electrons observed had an energy smaller than 100 Mev. Most of the electrons observed were well within the region where the density effect should be observed. In fact, many electrons had energies so great that there was still a solid core of particles in the shower as it passed through the bottom of the chamber after it had already traversed an inch of lead. This indicated that the particles of which the shower is composed are very energetic since they scattered very little in the lead. The particle initiating such a shower probably had an energy exceeding 1 Bev.

Figure 3 is a block diagram showing the ionization distribution for mesotrons. The weighted average mesotron ionization is 12.1 ± 0.3 drops/

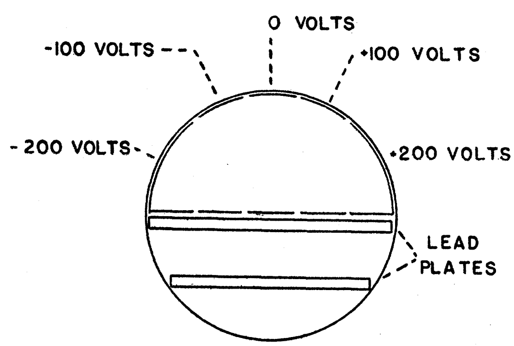


FIG. 2. Front view of the cloud chamber showing the lead plates and the electrodes that supply the clearing field.

[9] T. N. Gautier and A. E. Ruark, Phys. Rev. 57, 1040 (1940).

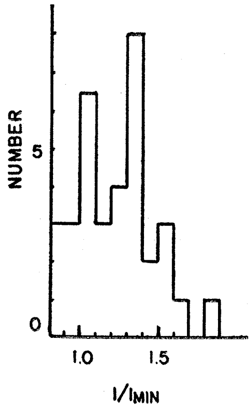


FIG. 3. Ionization distribution for mesotrons. The number of observed tracks is plotted as a function of the relative ionization.

cm. The observed probable deviation of a single observation is ± 14 percent. The spread in observed values of the ionization is due to the statistical variations in the ionization, the spread in energy of the mesotrons, and experimental uncertainties. The first two can be calculated and the last estimated. The statistical uncertainty is $\pm 0.67/N$, where N is the number of primary events or about half the observed number of drops.[10] An average track has about 100 drops so that its statistical uncertainty would be about ± 10 percent.

The energy distribution[11] of the mesotrons results in an ionization distribution. This distribution is asymmetric but can be approximated by a Gaussian curve with a probable deviation from the mean of about ± 6 percent of the central value. The experimental uncertainties that might result in random errors probably amount to about ± 5 percent. Hence the expected distribution in observed values would result in a probable error of $\pm(10^2+6^2+5^2)^{\frac{1}{2}} = \pm 13$ percent, which compares satisfactorily with the observed value of ± 14 percent. The above analysis indicates that the random experimental uncertainties are smaller than statistical uncertainties and that the expected probable error of a single observation in the case of electron tracks is, therefore, not appreciably greater than the statistical uncertainty.

For the minimum ionization we get 12.1/1.12 or 10.8 drops/cm. This is the value to which the ionization by electrons is compared.

Figure 4 is a block diagram showing the ionization distribution for electrons. If we omit for the present those points representing ionization above approximately 2.0 I_{min}, we see that the distribution appears to be symmetrical and the mean value is 1.45 I_{min}. The probable deviation of a single observation from the mean is ± 10 percent. Since it is believed that the probable error resulting from statistical and experimental uncertainties is ± 10 percent, the electron-ionization distribution seems to represent observations of a single-valued quantity. This is consistent with the prediction that all electrons with $E > 100$ Mev should have the same value for probable specific ionization.

The points corresponding to higher ionization cannot belong to the same group of observations of a single-valued quantity since they have no counterpart in the low ionization region. Nor can they be reasonably explained by assuming that the probable ionization loss continues to increase with increasing energy since the sea level electron spectrum is certainly a monotonically decreasing function of the energy. The most probable explanation is that heavily ionized tracks result from pairs produced in the upper wall of the counter above the cloud chamber. In order that the pair be unresolved in the cloud chamber, the initial angular separation of the two particles

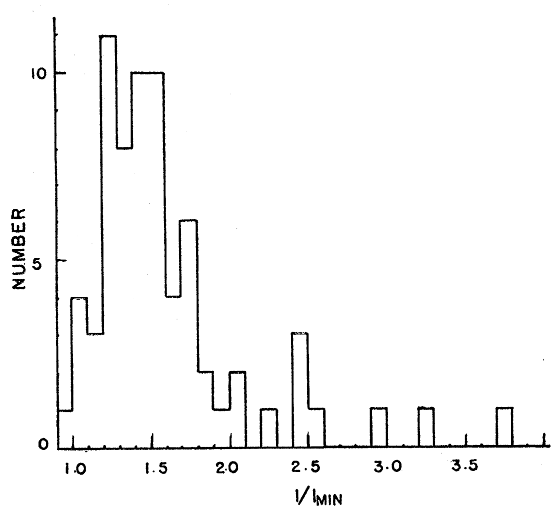
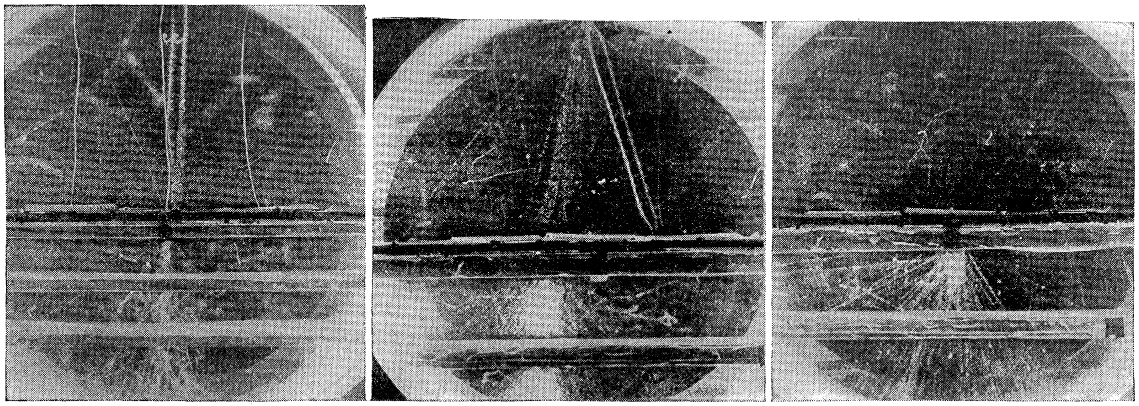


FIG. 4. Ionization distribution for electrons. The number of observed tracks is plotted as a function of the relative ionization.

[10] P. Kunze, Zeits. f. Physik **83**, 1 (1933).
[11] P. M. S. Blackett, Proc. Roy. Soc. **A164**, 257 (1938).



(a) (b) (c)

FIG. 5. Cloud-chamber photographs of unusual events, as described in the text.

must be small and the separation should not be appreciably increased by subsequent scattering in the material through which they pass. Both of these conditions will be fulfilled if the energy of the pair-producing gamma-ray is great enough. Since the average angle of emission of an electron of energy U is μ_e/U, the angular separation of the electron and positron depends on how the energy of the gamma-ray is divided between them. For gamma-ray energies above 10^8 ev all divisions of the energy of the pair-producing gamma-ray between the positron and electron are about equally probable except a division in which one particle takes off less than 10 percent of the energy. The latter case is much less probable. In this experiment we are concerned only with particles having an energy of at least 200–300 Mev, so that the average separation of the two particles would be of the order of 10^{-3} radians and the scattering in the upper glass wall of the chamber would not be enough on the average to resolve those of energy greater than 300 Mev. The showers associated with the "heavily ionizing" particles indicated that they had energies of at least this amount.

If we consider only gamma-rays in the energy range 3×10^8 to 10^{10} ev, we can calculate the probability that a pair will be produced in the material above the cloud chamber. There were effectively 0.105 radiation units of material above the chamber and the cross section for pair production is $\sim$0.6 for 3×10^8 ev and $\sim$0.8 for 10^{10} ev[1]. The number of gamma-rays that produce pairs, $1-e^{-\sigma t}$, then, varies from 6 to 8 percent in this energy range. Shower theory predicts that the ratio of the number of quanta to electrons is 1.7,[12] so that we would expect 10–12 percent of the observed showers to result from unresolved pairs. Since 10 percent of the shower-producing particles displayed heavy ionization, this seems to be a reasonable explanation for the observed results. If so, we may conclude that the density effect as calculated by Halpern and Hall is real, and that the ionization by high energy particles takes on a constant value independent of the energy.

4. SINGULAR EVENTS

Several interesting pictures, not directly connected with the experiment, were taken. The first (Fig. 5a), one of those taken in air, is a photograph of the track of a particle that ionized above five times as much as an average mesotron and also seems to have produced a huge shower in the lead below. The delta-ray near the top of the track gives slight evidence that the particle is moving downward and is not the result of a nuclear explosion in the lead. Other possible explanations are that it is an extremely high energy electron if no dielectric absorption effect exists, or several coincident electrons, or that it is a negative proton giving up all of its energy in interacting with the lead plate.

The second (Fig. 5b) is a huge shower which is

[12] W. Heisenberg, *Cosmic Radiation* (Dover Publications, New York, 1946), p. 24.

initiated either in the upper wall of the chamber or in the counter just above. This picture is unusual, not only because of the size of the shower, but also because of the associated proton that stops in the first lead plate.

The third (Fig. 5c) is a picture of a mesotron shower. This shower differs in its nature from all the others because its particles do not spread out from a central core as the shower progresses, but each particle goes through the second lead plate without multiplying. Most of these particles are heavier than electrons and several may be specifically identified as mesotrons. It may be noted that there are about four particles in the top of the chamber which seem to converge toward the point where the shower begins. One of these may have been the initiating particle, though the shower may have been started by a non-ionizing particle such as a neutron.

The author wishes to express great appreciation to Dr. Wayne E. Hazen for suggesting the problem and for many very helpful discussions.

PHYSICAL REVIEW VOLUME 72, NUMBER 10 NOVEMBER 15, 1947

The Shape of X-Ray Diffraction Lines from Colloidal Magnesium Oxide

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(Received July 10, 1947)

The broadened diffraction lines from colloidal particles have shapes which depend on the particle size and shape and on the geometrical features of the experiment. An analytical method is developed for eliminating the effect of the geometry of the experiment, thereby giving the shape of the diffraction line. The method is applied to the 200, 220, and 222 lines from colloidal magnesium oxide. The shapes of these diffraction functions in the low intensity regions are not sufficiently accurate to permit the determination of particle shape. The relative half-intensity breadths of curves give best agreement with the values to be expected for cube-shaped particles. The particle size, determined from the Scherrer equation, is 140 angstrom units, and the average deviation from this value is 3.1 percent.

I. INTRODUCTION

MURDOCK[1] gives a theoretical treatment of the breadths and shapes of the x-ray diffraction lines from colloidal powders of the cubic symmetry class. The purpose of the present paper is to give a method for calculating ideal line shapes from experimentally measured line shapes and to apply this method to several diffraction lines. Many investigations have been made on the breadths of broadened diffraction lines, but the shapes of the lines have not been measured because of the difficulty of correcting the measured shape for the effect of experimental conditions.

II. METHOD OF SOLVING FOR THE IDEAL DIFFRACTION FUNCTION

The procedure used in these experiments has been suggested by Jones.[2] For a given diffraction line a correction curve, $f(y)$, is measured, using a powder containing particles larger than 1000 angstrom units. An uncorrected diffraction curve, $\phi(x)$, is measured, using a colloidal powder of the same material. Jones has shown that these measured functions are related to the ideal diffraction function, $F(y)$, by the integral equation:

$$\phi(x)=\int_{-\infty}^{\infty} f(y)F(x-y)dy=\int_{-\infty}^{\infty} f(x-y)F(y)dy.$$

Knowing the functions $\phi(x)$ and $f(y)$ from experiment, the solution of the equation for $F(y)$

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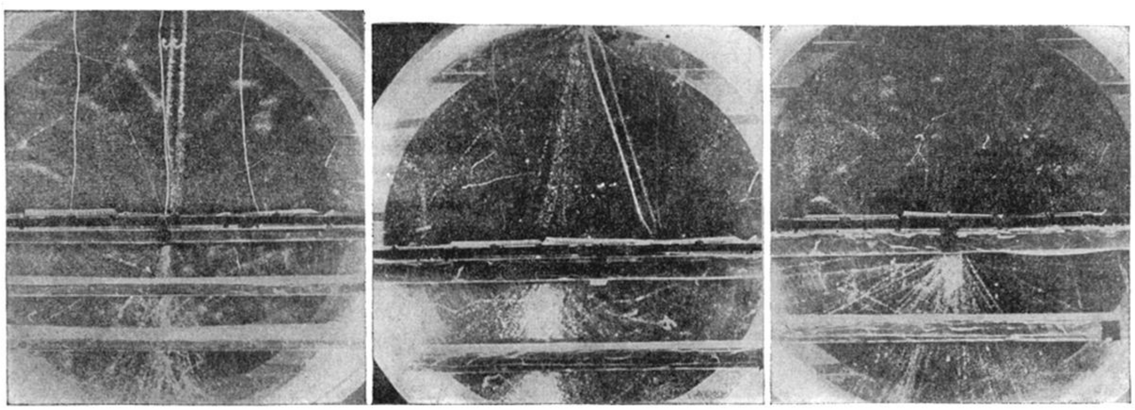
[1] C. C. Murdock, work not yet published in full but some of the results are given in Phys. Rev. **63**, 223 (1943).

[2] F. W. Jones, Proc. Roy. Soc. London **166**, 16 (1938).



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