REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 1 JANUARY, 1949

Electrons and Photons in Cosmic Rays*

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I. INTRODUCTION

IT has been known for some time that part of the electronic component of cosmic rays arises from the decay of mesons and from other secondary processes of these particles. It has also been pointed out repeatedly that while these phenomena can account for all of the electrons and photons present at sea level, an additional source of electronic radiation is necessary to explain the variation of the number of electrons and photons with altitude. Two possibilities have been considered, namely, (1) that high energy electrons or photons are incident upon the top of the atmosphere and (2) that high energy electrons or photons are created in the atmosphere by a primary radiation which is rapidly absorbed.

Lately some experimental results have been obtained which strongly support the second hypothesis. It is the purpose of the present paper briefly to describe these results and to discuss their intrinsic significance as well as their bearing on the general interpretation of cosmic-ray phenomena.

II. PRODUCTION OF ELECTRONIC RADIATION IN NUCLEAR INTERACTIONS

Occasional reference is found in the literature to cloud-chamber pictures which indicate the simultaneous appearance of electrons and of heavily ionizing or penetrating particles.[1] Only recently, however, has the fact been recognized that the production of electronic radiation is one of the main results of high energy nuclear interactions. The experiment which first led to this conclusion was performed by Bridge, Rossi, and Williams,[2] by means of the arrangement shown in Fig. 1. A tray of Geiger-Mueller counters and a cylindrical ionization chamber were placed one above the other with a 15-cm thick lead absorber between them. Pulses of the ionization chamber, which were greater in size than a given amount and which occurred simultaneously with the discharge of one of the Geiger-Mueller tubes, were recorded photographically so that, from the size of each pulse, the amount of ionization released in the chamber could be computed. At sea level, with the instrument described, about 0.25 coincidence per hour was recorded, in which the ionization pulse was greater than the pulse produced by the passage through the chamber of 55 lightly ionizing particles. The coincidence rate increased to almost one hundred per hour when the instrument was operated at 30,000 feet, aboard a B-29.

We shall first discuss the possibility that the observed coincidences were produced by high energy electrons traversing the upper tray and initiating in the lead shield a shower which discharged the chamber underneath. The energy required for this process is about 5×10^{11} ev. Electrons of this energy produce showers of about 5000 particles in traversing 3 cm of lead. Thus, if high energy electrons were responsible for a large fraction of the coincidences observed with 15 cm of lead, one should obtain a number of coincidences comparable with that observed under 15 cm of lead by reducing the lead thickness to 3 cm and increasing the bias by a factor of about 100. An experiment carried out at 14,000 feet showed that this is not the case. Actually, an increase of the bias by only a factor of three was required to bring the number of coincidences observed with 3 cm of lead back to the value observed at the original bias with 15 cm of lead.[3] This proves that the number of high energy electrons in the atmosphere is not sufficiently large to explain the observed coincidences.

Let us consider next the possibility that the coincidences were caused by mesons which produced in the lead either high energy electrons by

* Assisted by the joint program of the Office of Naval Research and the Atomic Energy Commission.

[1] See, for instance, M. J. Daudin, Comptes Rendus **218**, 830 (1944); G. D. Rochester, Proc. Roy. Soc. **187**, 464 (1946).

[2] H. Bridge, B. Rossi, and R. W. Williams, Phys. Rev. **72**, 257 (1947).

[3] H. Bridge.

collision processes or high energy photons by radiation processes. Events of these kinds might possibly account for the coincidences observed at sea level. However, they cannot account for any appreciable fraction of the coincidences observed at high altitude because the number of coincidences increases by a factor of several hundreds from sea level to 30,000 feet while the total number of mesons increases by only a factor of 5 or 6, and the number of high energy mesons presumably increases by an even smaller factor.

It thus appears that the coincidences observed at high altitude must be attributed either to ionizing particles which are capable of producing bursts after traversing large thicknesses of lead and increase with altitude much faster than ordinary mesons, or to air showers, incident at large zenith angles, which strike the ionization chamber without traversing the entire thickness of lead placed between the chamber and the counters.

To obtain further information on the origin of the coincidences, an experiment was carried out by Bridge, Hazen, and Rossi at 14,000 feet.[4] In this experiment the lower part of the lead absorber was replaced by a number of lead plates placed inside a cloud chamber, which was triggered by the coincidences between the Geiger-Mueller counter tray and the ionization chamber. The experimental arrangement is shown in Fig. 2. With this instrument many pictures were obtained showing ionizing particles which initiate showers in one of the lead plates inside the cloud chamber, after traversing uneventfully five inches of lead placed between the Geiger-Mueller counters and the cloud chamber as well as some of the lead plates inside the cloud chamber. Most of the shower particles appeared to be electrons. However, in about two-thirds of the pictures either heavily ionizing particles (presumably low energy protons) or penetrating lightly ionizing particles (presumably high energy protons or mesons) were observed. It is quite possible that particles of this kind were present as well in the pictures classified as pure electron showers, but were not detected.

Other cloud-chamber pictures were obtained,

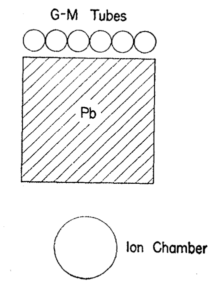


FIG. 1. Experimental arrangement used by Bridge, Rossi, and Williams to investigate burst production by penetrating particles.

indicating events in which air showers were apparently responsible for the coincidences between the ionization chamber and the Geiger-Mueller counters. Events of this type were about equally as frequent as those in which shower production by penetrating particles apparently caused coincidences. The number of coincidences caused by penetrating particles as compared with the number of those produced by air showers was presumably much greater in the original Geiger-Mueller counter-ionization chamber experiment than in the Geiger-Mueller counter-cloud-chamber-ionization chamber experiment, since, in the former, the ionization chamber was more effectively shielded by the lead absorber. Thus the rapid increase with altitude of the coincidence rate observed with the arrangements shown in Fig. 1 can be explained only by a rapid increase with altitude of the shower production by penetrating particles.

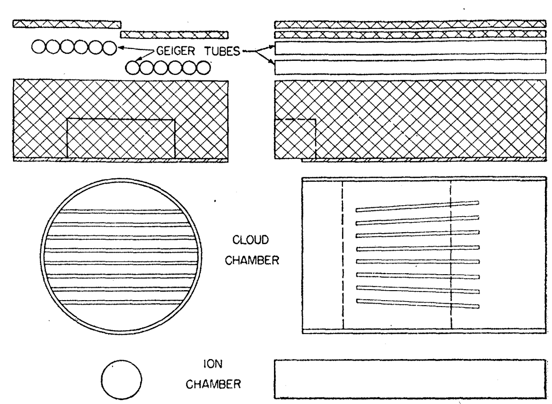
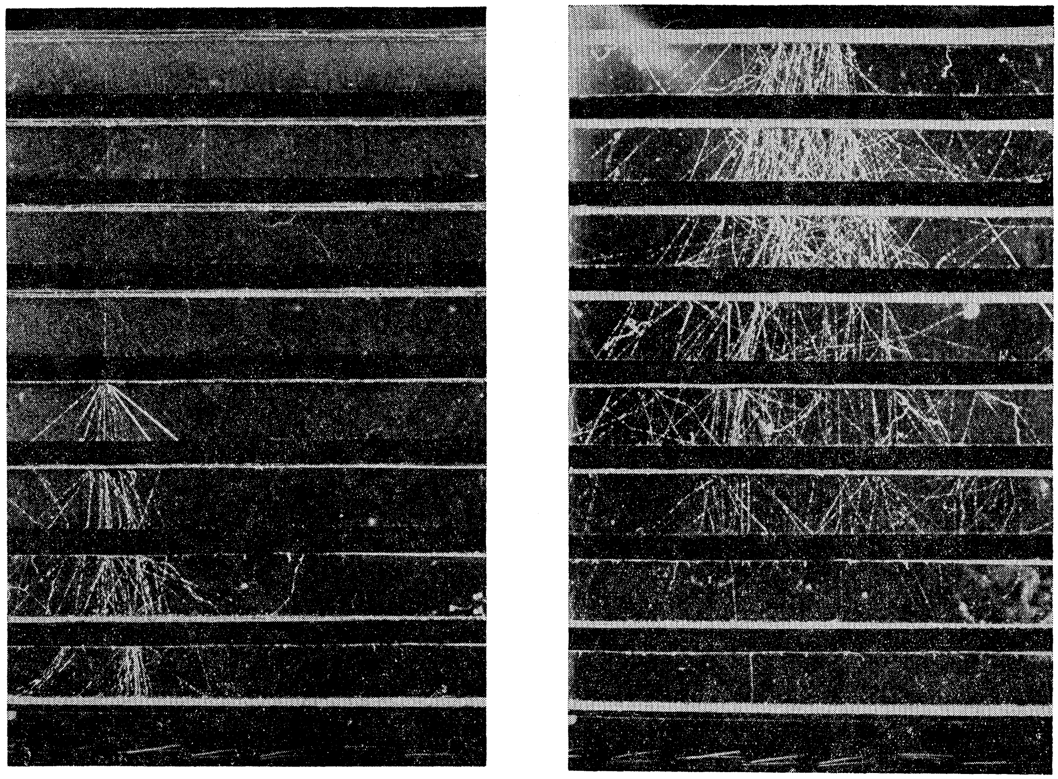


FIG. 2. Experimental arrangements used by Bridge, Hazen, and Rossi to investigate burst production by penetrating particles.

[4] H. Bridge, W. E. Hazen, and B. Rossi, Phys. Rev. **73**, 179 (1948), see also H. Bridge and W. E. Hazen, Phys. Rev. **74**, 579 (1948).



(a) (b)

FIG. 3. Four pictures obtained by C. Y. Chao at M.I.T. by means of a cloud chamber containing 8 lead plates ½ inch thick. (a) An ionizing penetrating particle undergoes a nuclear interaction in which several heavily ionizing particles, several penetrating particles, and an electron shower are produced. (b) A large shower containing electrons and penetrating

The experimental evidence presented above results in the following picture.

(1) There exist particles capable of producing one or more electrons or photons after traversing uneventfully several inches of lead.

(2) The interactions in which this production of electrons or photons takes place are of nuclear rather than of electromagnetic character, as shown by the simultaneous appearance of heavily ionizing and/or penetrating particles.

(3) The frequency of occurrence of these interactions increases with altitude much more rapidly than the number of ordinary mesons. Hence most of the interactions observed at high altitude are produced by particles different from ordinary mesons.

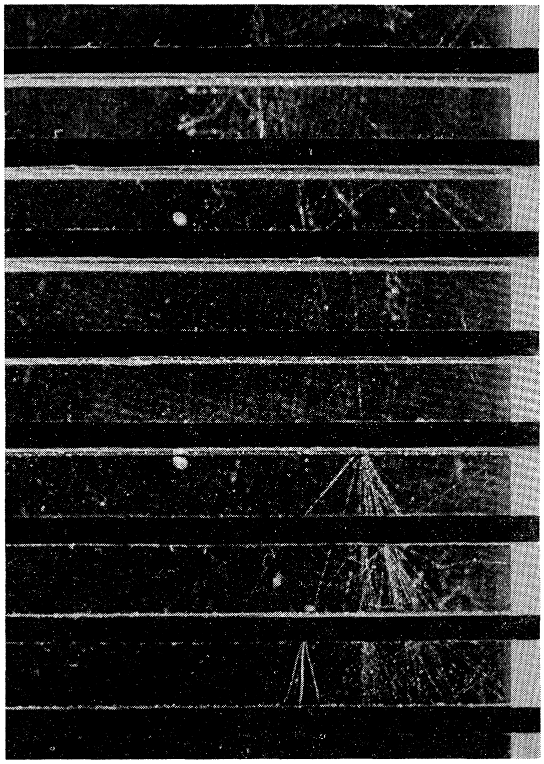
It is reasonable to assume that the particles in question are mainly high energy protons, either belonging to the primary cosmic radiation or released in collisions of primary cosmic rays with atomic nuclei in the atmosphere. Interactions of a kind similar to those produced by high energy protons should be prouced also by high energy neutrons, if such neutrons are released in the collisions of primary cosmic rays with matter. Finally, the possibility must be mentioned that "heavy mesons" of the kind detected in photographic emulsions by Occhialini, Powell, and their collaborators may be partly responsible for the nuclear interactions in which high energy electrons or photons are produced.

Evidence for secondary processes in which electron showers and particles heavier than electrons are produced simultaneously has also been obtained by Fretter,[5] and by Chao[6] with cloud chambers operated at sea level and triggered by various arrangements of Geiger-Mueller counters. Some of the pictures obtained by Chao are shown in Fig. 3.

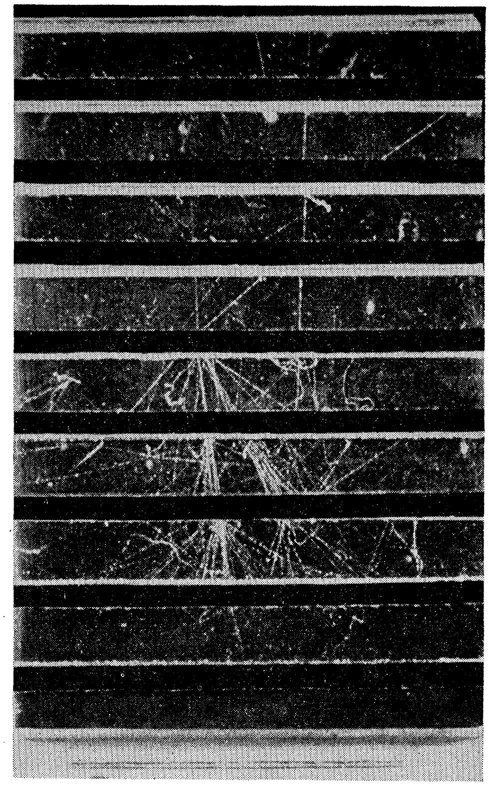
An important question is whether nuclear interactions give rise to single electrons or pho-

[5] W. M. Fretter, Phys. Rev. **73**, 41 (1948).

[6] C. Y. Chao.



(c)



(d)

ionizing particles. (c) An ionizing penetrating particle produces a nuclear interaction which gives rise to an electronic shower as well as to at least two particles of non-electronic nature, one of which produces a secondary nuclear disintegration. (d) An electron shower with two separate cores, believed to be initiated by a nuclear interaction.

tons, or to several such particles simultaneously. The results obtained by Chao, even though of a preliminary nature, seem to indicate that at least sometimes multiple production takes place. The clearest example is that shown in Fig. 3d, where one sees distinctly a shower with two separate cores diverging at an angle of about 20°. The energies in each of the two cores is about 10^9 ev. It is extremely unlikely that angular divergence at production or scattering of high energy electrons may cause a shower originating from a single electron or photon to acquire this peculiar structure.

The only quantitative information which exists so far on the altitude variation of the rate of production of electronic radiation by nuclear interaction comes from coincidence experiments performed with the arrangement shown in Fig. 1. The results of these experiments are given in Fig. 4.[7] Within the experimental errors, the increase in the rate of coincidences with decreasing atmospheric depth, x, can be represented by the law: $\exp(-x/L)$ with $L=125$ g cm^{-2}. It is fully realized that the results of the measurements considered here might have been appreciably affected by air showers. Experiments to test this point are in preparation. Provisionally, we shall disregard the possible influence of air showers on the altitude dependence of the observed coincidences and shall assume that the exponential law written above represents the atmospheric absorption of the radiation responsible for the nuclear interactions in which high energy electrons or photons are produced.

This assumption is strengthened by some measurements carried out recently by Tinlot with a coincidence arrangement of Janossy's

[7] H. Bridge, as reported by B. Rossi in Rev. Mod. Phys. **20**, 537 (1948).

type.[8] This arrangement is believed to detect the occurrence of nuclear interactions in which showers of penetrating particles are produced. Some of Tinlot's data are plotted in Fig. 4 along with the results of the ionization chamber experiment on burst production by penetrating particles. One sees that the two phenomena show a very similar altitude dependence, as one should expect if they are both the result of high energy nuclear interactions.

III. PRIMARY ELECTRONS AND PHOTONS

It was stated by Schein *et al.*, as a result of some Geiger-Mueller counter experiments carried out at high altitude with balloons, that high energy electrons or photons do not appear to be present in large numbers in the primary cosmic radiation.[9] Recently this conclusion has been submitted to a more quantitative test by Hulsizer and Rossi.[10] The instrument used by these experimenters consists of an ionization chamber covered with a 1-inch thick lead shield and borne aloft by balloons. A high energy electron or photon incident upon the lead produces a shower which can be detected by the resulting ionization burst in the chamber. With this instrument, some preliminary data were obtained at an altitude of 90,000 feet, where the residual atmospheric depth is 20 g cm^{-2}. The bursts observed at this altitude can be explained by the nuclear interactions of primary protons discussed in Part II. If one assumes, however, that they are produced by high energy electrons or photons, one finds an upper limit of one percent for the number of these particles at 90,000 feet relative to the total number of primary cosmic rays. The bias setting was such as to place a lower limit of about 10^{10} ev for the energy of the electrons or photons which could be detected.[11] In further experiments now in preparation, an attempt will be made to detect electrons and photons of lower energy and to determine the effect of shower production by nuclear interactions of primary protons. Since, however, the detectable energy in the present experiments is of the same order of magnitude as the average energy of primary cosmic rays, it already appears that primary electrons or photons are not the main source of the electronic radiation observed in the atmosphere. In what follows we shall assume that *no electrons or photons are present in the primary radiation and that the electronic component of cosmic rays arises entirely from the decay of ordinary mesons, from the known electromagnetic interactions of mesons and protons, and from the nuclear interactions discussed in Part II.*

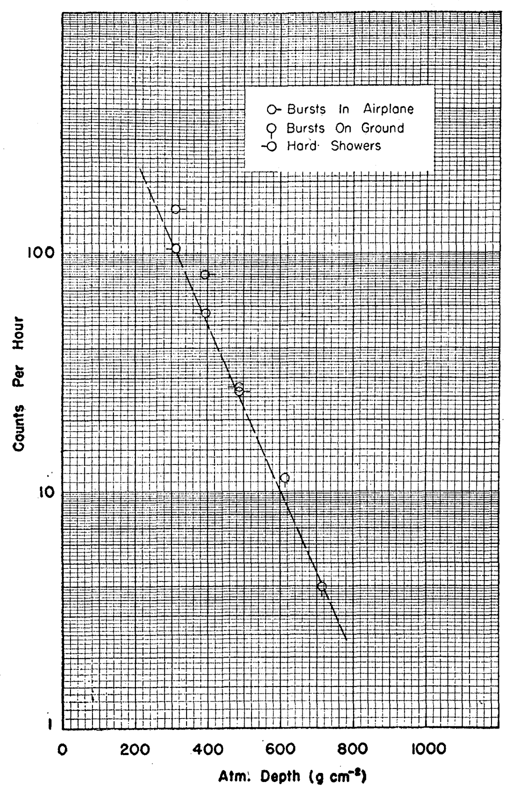


FIG. 4. Hard showers and burst production by penetrating ionizing particles as a function of atmospheric depth.

IV. ANALYSIS OF THE ELECTRONIC COMPONENT IN THE ATMOSPHERE

The experimental data on the electronic component in the atmosphere will now be analyzed to investigate whether or not they are consistent

[8] J. Tinlot, Phys. Rev. **73**, 1476 (1948).

[9] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 615 (1941).

[10] R. I. Hulsizer and B. Rossi, Phys. Rev. **73**, 1402 (1948).

[11] The value for the minimum energy stated in the original paper (4.5×10^9 ev) had been computed from the shower theory as presented by Rossi and Greisen [Rev. Mod. Phys. **13**, 240 (1941)]. The value quoted here (10^{10} ev) derives from the more accurate calculations of Belenky (see reference 17 below).

with the hypothesis stated above and, if so, to obtain more information on the phenomenon of the production of electronic radiation by nuclear interactions. We shall consider first the data concerning the *total intensity* of the electronic radiation at various altitudes and shall discuss next the data relative to the number and energy distribution of high energy electrons and photons. In this analysis it will always be understood, when not differently stated, that the particles considered are those incident *per second and per unit solid angle in nearly vertical directions.* The data presented refer to geomagnetic latitudes around 50°.

(1) The Total Intensity of the Electronic Component

The experimental data, from which the number of electrons at various altitudes can be computed, have been analyzed by the writer in a recent article.[12] The result of this analysis is shown by the curve marked $k^{(e)}$ in Fig. 5. The abscissa represents atmospheric depth in g cm^{-2}. The ordinate represents, on a logarithmic scale, the energy dissipated at the depth x in one gram of air by electrons of all energies incident in the vertical direction. In the evaluation of the data presented in Fig. 5 the computed number of electrons arising from the collision processes of meson has been subtracted from the total number of electrons observed. (This represents a small correction at all depths.) Since radiation processes of mesons and collision or radiation processes of protons are negligible compared with the other sources of electronic radiation, $k^{(e)}$, according to our assumptions, represents the intensity of the electrons which arise from the decay of mesons and from nuclear interactions. One may estimate that the uncertainty in the value of $k^{(e)}(x)$ varies from about 10 percent in the lower atmosphere to about 30 percent at depths around 100 g cm^{-2}. The total energy dissipated in a column of atmosphere of one cm^2 cross section by electrons incident in the vertical direction (exclusive of collision electrons) is obtained by integrating the function $k^{(e)}(x)$ and has the value:

$$W^{(e)} = 285 \cdot 10^6 \text{ ev cm}^{-2} \text{ sec.}^{-1} \text{ sterad}^{-1}{}^{12}.$$

[12] B. Rossi, Rev. Mod. Phys. **20**, 537 (1948).

The contribution of electrons from meson decay processes to the total electron intensity may be computed with the following procedure:[13]

(a) One first computes the energy $k_d^{(m)}$ lost through decay by the meson beam in one gram of air at the various depths. This quantity is given, with good approximation, by the equation

$$k_d^{(m)}(x) = (\mu c/\tau\rho) I_v^{(m)}(x), \tag{1}$$

where x is the atmospheric depth, ρ the density of air, c the velocity of light, μ the mass and τ the mean lifetime of mesons, and $I_v^{(m)}$ the vertical intensity of the meson beam (number of mesons per cm^2, second and steradian). Equation (1) shows that the computation of $k_d^{(m)}$ requires knowledge at the total intensity of mesons, but does not require knowledge of their energy distribution.

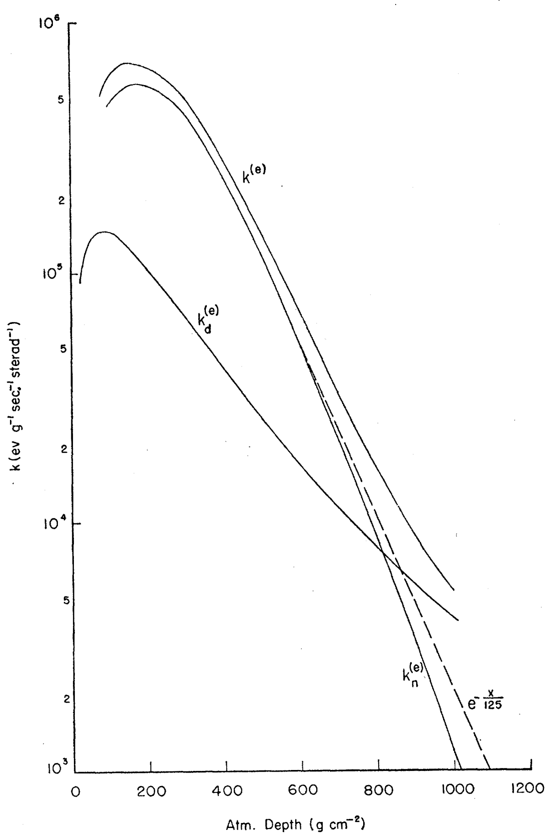


FIG. 5. The contributions of electrons from meson decay ($k_d^{(e)}$) and from nuclear interactions ($k_n^{(e)}$) to the total electron intensity ($k^{(e)}$).

[13] B. Rossi and K. I. Greisen, Phys. Rev. **61**, 121 (1942)

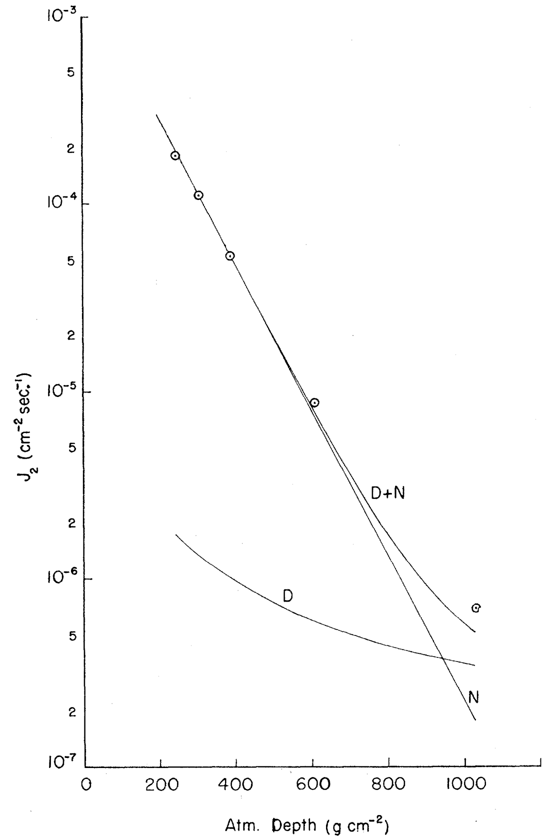


FIG. 6. Integrated intensity of high energy electrons and photons arising from meson decay (D) and from nuclear interactions (N). The ordinate represents number of particles traversing a sphere of 1-cm^2 cross section per second.

(b) One then computes the fraction α of the energy $k_d^{(m)}$ which goes into decay electrons (it is assumed that no photons are produced by the decay of mesons). If one takes into consideration the fact that the decay electrons are emitted in random directions in the frame of reference in which the meson is at rest, one can easily show that the fraction α is equal to the average energy of the electrons arising from the decay of mesons at rest, divided by the rest energy of mesons μc^2. Unfortunately, the average energy of decay electrons is not yet known experimentally. In the calculations presented here α was taken as equal to $\frac{1}{4}$. This value was considered as the best guess at the time that the calculations were made, but more recent experiments[14] indicate that the actual values of α is probably larger than $\frac{1}{4}$.

(c) The function $\alpha k_d^{(m)}(x)$ represents the energy of the decay electrons *produced* in one gram of air at the depth x. From this function one must now obtain the function $k_d^{(e)}(x)$ representing the energy dissipated in one gram of air by electrons arising from the cascade multiplication of decay electrons produced at higher levels. This is done by means of a mathematical transformation which involves the application of the shower theory and requires knowledge of the energy distribution of the electrons arising from the disintegration of mesons in flight. Fortunately the results of the computation do not depend critically on the assumed shape of the electron spectrum. Thus the existing uncertainty in this spectrum does not represent a serious source of error. In the calculations presented here, the energy spectrum of decay electrons was computed by making use of the energy distribution of mesons at various altitudes given by Sands[15] and by assuming that all electrons arising from the decay of mesons at rest have an energy equal to $\mu c^2/4$.

Computed values of the function $k_d^{(e)}(x)$ are shown in Fig. 5. By subtracting $k_d^{(e)}(x)$ from $k^{(e)}(x)$, one obtains a quantity $k_n^{(e)}(x)$ which, according to our assumptions, represents the energy dissipation of electrons arising from cascade multiplication of electrons or photons produced in nuclear interactions. In the lower part of the atmosphere these electrons should be in equilibrium with the radiation from which they originate and therefore $k_n^{(e)}(e)$ should vary with depth as $\exp(-x/125)$, as shown by the dashed line. The deviation of the function $k_n^{(e)}(x)$ from this exponential behavior is not considered as significant, because of the large uncertainties of the analysis.

According to the assumption made, the total energy of the decay electrons produced in a column of air of 1-cm^2 cross section, $W_d^{(e)}$, is one-quarter of the energy released in this column by the decay of mesons. The latter has been estimated to be $190\cdot 10^6$ ev cm^{-2} sec.$^{-1}$ sterad^{-1}.[12] Consequently, $W_d^{(e)}$ has the value $W_d^{(e)}=47\cdot 10^6$ ev cm^{-2} sec.$^{-1}$ sterad^{-1}. The total energy of the electronic radiation arising from nuclear interactions is then given by

$$W_n^{(e)}=W^{(e)}-W_d^{(e)}$$
$$=238\cdot 10^6 \text{ ev cm}^{-2}\text{ sec.}^{-1}\text{ sterad}^{-1}.$$

[14] R. W. Thompson, Phys. Rev. **74**, 490 (1948).

[15] M. S. Sands, M.I.T. thesis (1948).

It is interesting to note that this energy is of the same order of magnitude as the total energy which goes into mesons and for which the following value has been found[12]

$$W^{(m)} = 289 \cdot 10^6 \text{ ev cm}^{-2} \text{ sec.}^{-1} \text{ sterad}^{-1}.$$

(2) Electrons and Photons of High Energy

Very little experimental data on electrons and photons of high energy in the atmosphere are available until now. Some information can be obtained from an experiment carried out by Bridge and Rossi,[16] who observed the rate of occurrence of bursts in an ionization chamber operated at various altitudes both unshielded and under a 2.5-cm thick lead shield. At all altitudes the counting rate was considerably greater with than without the lead shield. Separate experiments showed that practically all bursts observed in an unshielded ionization chamber of the type used were due to nuclear disintegrations and that the lead above the chamber did not affect appreciably the number of these disintegrations. Therefore, apart from a small correction due to shower production by penetrating particles, the increase in burst rate caused by the lead may be taken as a measure of the number of electrons and photons incident upon the instrument and having sufficiently high energy to produce showers of the size indicated by the observed ionization bursts. The experimental results, expressed in number of particles per cm^2 and second, are shown by the circles in Fig. 6. Since the instrument did not have a pronounced directional selectivity, the data may be interpreted to represent the *integrated intensity*, rather than the vertical intensity, of electrons and photons. The difficulty in defining the "effective area" of the detector, while it does not affect the relative values of the intensity at the different depths, introduces a considerable uncertainty in the absolute value of the intensity at any particular depth. From the size of the pulses and from the shower theory, as modified by Belenky,[17] the minimum energy of the electrons and photons detected in this experiment was estimated to be $1.1 \cdot 10^{10}$ ev. It is difficult to evaluate the accuracy of such an estimate.

[16] H. Bridge and B. Rossi, Phys. Rev. **71**, 379 (1947).
[17] S. Belenky, J. Phys. U.S.S.R. **8**, 305 (1944).

The curve marked D in Fig. 6 represents the integrated intensity of electrons and photons of energy larger than $1.1 \cdot 10^{10}$ ev arising from the decay and from collision processes of mesons. In the computation of this curve, it was assumed that the electrons arising from the disintegration of mesons at rest have an energy equal to $\mu c^2/4$ and that the intensity of electrons and photons depends on the zenith angle θ according to a $\cos^2\theta$ law. It appears that the relative contribution of electrons and photons from decay processes is important only near sea level.

The curve marked N represents a tentative estimate of the integrated intensity of high energy electrons and photons arising from nuclear interactions. It is computed on the assumptions that the radiation responsible for the nuclear interactions varies with depth according to the law $\exp(-x/125)$ and that in these interactions electrons with an integral energy spectrum of the type const.$/E^{1.8}$ are produced. (The shape of the curve N depends mainly on the absorption law of the primary radiation and only slightly on whether electrons or photons are created and on the form of the energy spectrum of these particles.) The curve N is adjusted to the experimental data at a depth of about 300 g cm^{-2}, at which the contribution of decay electrons is negligible.

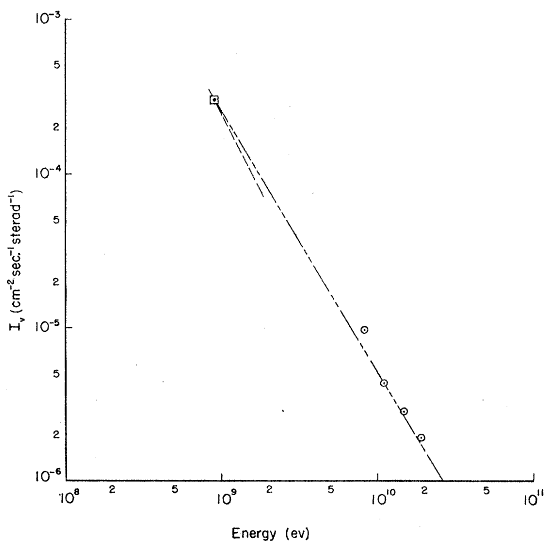


FIG. 7. Preliminary data on the integral energy spectrum of high energy electrons and photons at 10,000 feet. The ordinate represents number of particles per cm^2, second and steradian in the vertical direction.

The curve $D+N$ is the sum of curves D and N. Comparison of this curve with the experimental points shows that our assumptions regarding the origin of the electronic component do not lead to any contradiction when their consequences are compared with the experimental data on the altitude variation of high energy electrons and photons.

In Fig. 7 some experimental data on the integral energy spectrum of electrons and photons at 10,000-feet altitude are presented. The point marked with a square represents the results of cloud-chamber observations of showers by Hazen.[18] The dashed line through this point indicates the energy dependence suggested by Hazen's observations. The points marked with circles are obtained from the ionization chamber experiments of Bridge and Rossi mentioned previously. Within the large experimental uncertainties, the integral energy spectrum of electrons and photons may be represented by a power law: const./E^γ, with a value for γ between 1.6 and 2. Since most of the electronic radiation at 10,000 feet originates from nuclear interactions, the energy spectrum of this radiation reflects the energy spectrum of the electrons or photons produced in these interactions. In fact, in the high energy region the two spectra have identical shapes if the production spectrum is represented by a power law. Thus an accurate measurement of the energy spectrum of electrons and photons in the atmosphere is of great interest.

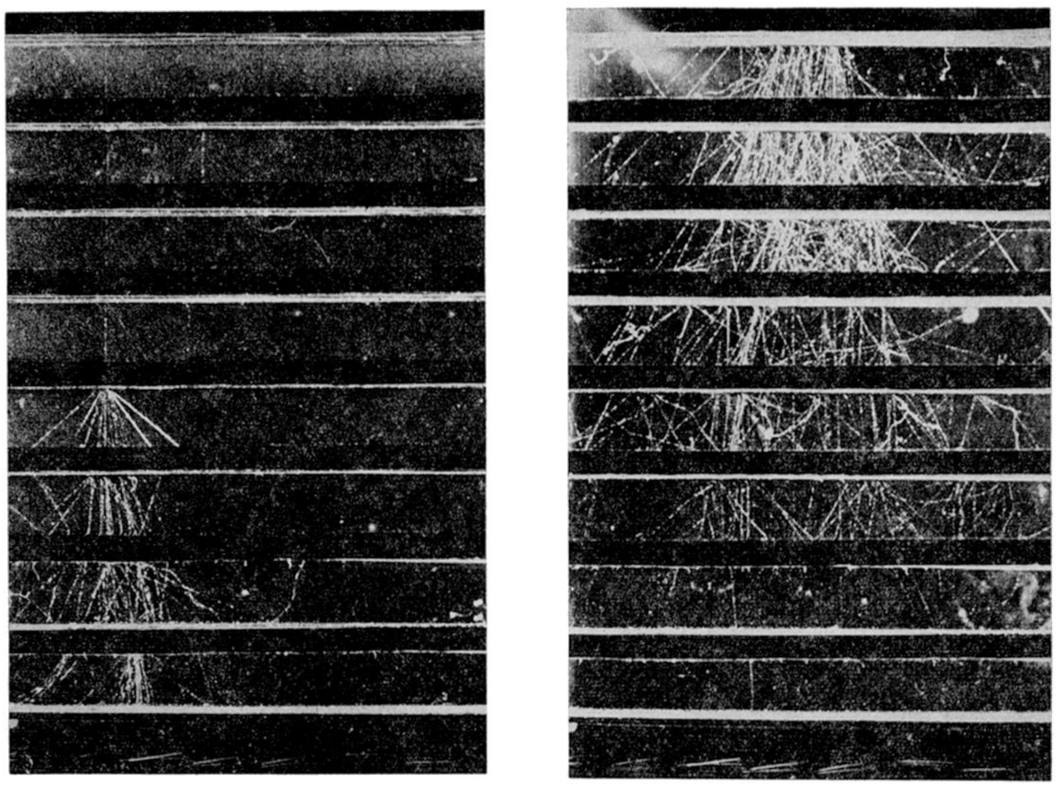
Another interesting quantity is the ratio of electrons to photons, because, from the knowledge of this ratio, it may be possible to determine whether electrons or photons are directly produced in the nuclear interactions. The results reported by Hazen, if taken at face value, would indicate that electrons are more numerous than photons, which would necessarily imply that electrons are the direct products of nuclear interactions. However, Hazen's results may be falsified by the fact that most photons of high energy follow paths very close to the paths of parent electrons and therefore may fail to be detected as separate shower-producing entities.

[18] W. E. Hazen, Phys. Rev. **65**, 67 (1944).

V. FINAL REMARKS

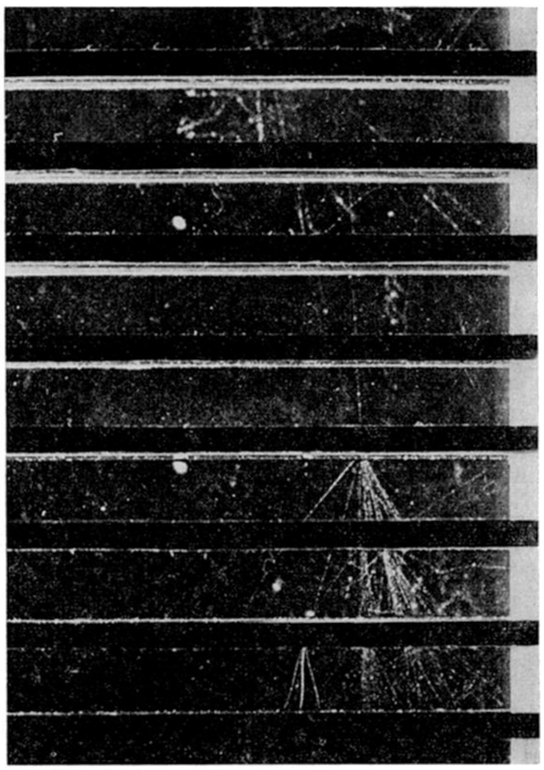
The analysis presented in Section IV shows that the hypothesis, according to which the electronic component of cosmic rays arises entirely from nuclear interactions and from secondary effects of mesons, does not lead to any obvious contradiction. It is necessary, however, to point out that some of the experimental data on which this analysis is based are still very crude. In particular, the computation of the intensity of the electronic radiation arising from the decay of mesons has an uncertainty which reflects the uncertainty in the experimental value for the average energy of decay electrons of mesons at rest. Actually, the value of this average energy on which our calculations were based does not coincide with the value that one would probably choose today, on the basis of the latest experiments.

It is reasonable to assume that the nuclear interactions which, according to our hypothesis, give rise to part of the electronic component of cosmic rays are the same in which mesons are produced. In fact, it is possible that the production of electronic radiation takes place through the intermediary of some kind of short lived mesons. Since the decay and other secondary effects of ordinary mesons are responsible for the rest of the electronic radiation, the origin of all electrons and photons is traced back to the same primary rays which are the origin of the meson component. These primary rays are generally assumed to be high energy protons. Here one encounters a difficulty already noted elsewhere, namely, that the east-west effect of the total cosmic radiation at high altitude seems to be smaller than one would expect if both electrons and mesons originate from a positively charged primary radiation. This conclusion is, of course, based upon the assumption that direction is preserved to a large extent in the chain of secondary processes that lead to the production of electrons. Theoretical and experimental arguments indicate that nuclear interactions give rise to secondary particles with a large angular spread. It is, however, still uncertain whether or not this effect affords a quantitative explanation of the difficulty mentioned above.



(a) (b)

FIG. 3. Four pictures obtained by C. Y. Chao at M.I.T. by means of a cloud chamber containing 8 lead plates $\frac{1}{2}$ inch thick. (a) An ionizing penetrating particle undergoes a nuclear interaction in which several heavily ionizing particles, several penetrating particles, and an electron shower are produced. (b) A large shower containing electrons and penetrating



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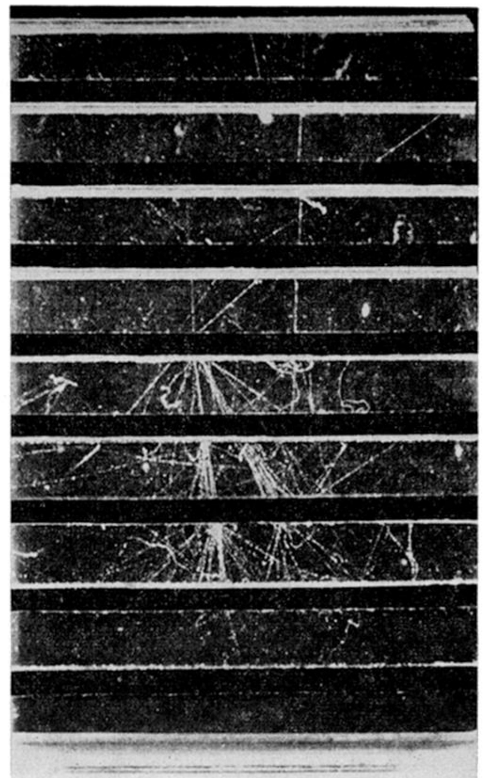

(d)

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