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The Behavior of High Energy Electrons in the Cosmic Radiation

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The behavior of electrons and photons of high energy is discussed in relation to the production of large bursts of cosmic-ray ionization, or Hoffmann *Stösse*, and the occurrence of nuclear "vaporizations." It is shown that the electrons from the disintegration of mesotrons have an importance equal to that of the cascade electrons. The number and size-frequency distribution of large showers (of a hundred or more rays) from thin and thick pieces of lead at sea level, and the variation with elevation of such showers are well accounted for by the action of electrons and photons from these two sources. It is unnecessary to invoke the direct production of bursts by penetrating rays by means of an explosion process. The behavior of showers of a few rays is likewise well accounted for. However, difficulties are encountered in explaining: (a) the relative numbers of bursts from large thicknesses of iron and lead, and (b) the occurrence of showers, from the air, which have a large number of rays per unit area. (See note added in proof page 261.) The hypothesis is advanced that the showers of heavily ionizing particles, or nuclear vaporizations, are produced by electrons and photons in the same range of energy as those which produce the large bursts. The identification of showers of heavily ionizing particles with Hoffmann *Stösse* is shown to be untenable. A determination of the absolute number of neutrons in the cosmic radiation at sea level is shown to be consistent with the supposition that these neutrons are produced in the nuclear vaporization process.

ONE of the most interesting aspects of cosmic-ray phenomena is the study of the interaction of radiation of such high energy with matter. The interactions of high energy photons and electrons with matter have been particularly interesting in the past, since the theoretically predicted behavior was, at first, thought to disagree with experience, and a limit to the application of the theory was thought to have been found. How this difficulty was resolved by the establishment of the existence of a new particle, the mesotron, and how the theoretical predictions were substantiated by direct measurements of the energy losses of fast electrons, is a familiar story to all of you. However, electrons and photons produce quite complicated effects, and it is of interest to see to just what extent these may be unraveled on the basis of our present knowledge. We therefore wish to discuss two classes of phenomena which, we believe, are the result of high energy electrons and photons, namely: the production of the large bursts of cosmic-ray ionization, and the occurrence of the showers of heavily ionizing particles which may be termed "nuclear vaporizations."

LARGE BURSTS OF COSMIC-RAY IONIZATION

Let us first consider the large bursts of ionization or Hoffmann *Stösse*. We have shown[1] that the number of bursts observed from a piece of lead a centimeter in thickness is reasonably well explained as the result of a number of electrons or photons falling upon the lead which then multiply according to the ordinary processes of the cascade theory. The energy distribution of the electrons or photons required to produce the observed size-frequency distribution of the bursts is also a reasonable one. Proper account was taken of the large fluctuations[2] which are important at small thicknesses of material, and it was shown that electrons of energies from about 2×10^9 volts to almost 10^{11} volts contributed to the number of bursts containing of the order of one hundred rays. The problem before us is to determine in what manner these electrons originate, whether they are primary or secondary and what produces them, and how they vary with elevation.

Electrons from the primary electron component

The simplest point of view to adopt is that these high energy electrons present in the atmosphere are the result of a primary electron component of the cosmic radiation. However, it is immediately obvious that this hypothesis does not harmonize with all the facts. There have been observed[3] large bursts at great depths below the

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[1] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **53**, 955 (1938).

[2] W. H. Furry, Phys. Rev. **52**, 569 (1937).

[3] F. Weischedel, Zeits. f. Physik **101**, 732 (1936). J. Clay, C. G.'T Hooft, L. J. L. Dey and J. T. Wiersma, Physica **4**, 121 (1937).

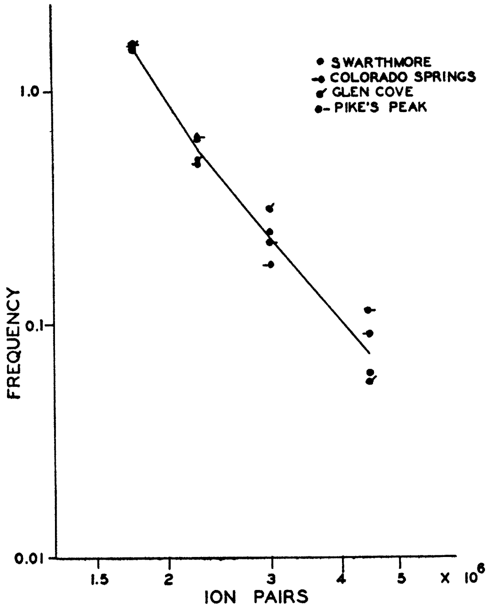

FIG. 1. Size-frequency distribution curves of large bursts for four elevations, reduced to sea level.

top of the atmosphere, depths to which it would be quite unreasonable to suppose that a primary electron component could penetrate.

We encounter a similar difficulty at altitudes above sea level. The observations of bursts up to the altitude of Pike's Peak[4] made with four centimeters of lead, that is, at the maximum of the Rossi curve for showers of about one hundred rays, may be summarized in the following way. Fig. 1 shows the size-frequency distributions of the bursts at four elevations reduced to a common basis by multiplying each distribution by a constant factor. It is evident that the distribution is independent of elevation except for this constant factor. The variation with elevation of the total frequency of bursts greater than a given size is shown in Fig. 2 on a logarithmic scale. The variation with elevation is not an exponential one, but the absorption coefficient increases considerably with increasing altitude. Now these two facts are inconsistent with the behavior of electrons propagated according to the cascade processes. For, suppose we take the distribution of electrons which produced the bursts at the elevation of Pike's Peak and ask how this distribution will be transmitted through the atmosphere to sea level. Now Nordheim[5] has shown that if we have an energy distribution of electrons of the form A/E^n, this distribution will be propagated unchanged in form, and can be represented, after traversing a distance x, by $Ae^{-\mu x}/E^n$, where μ is related by a simple expression to the exponent n. We can analyze the electron distribution at Pike's Peak into a series of terms of this form, and, since the diffusion equations of the cascade theory are linear, each term will be absorbed exponentially. The observations show us that the shape of the electron distribution is not altered in going from Pike's Peak to sea level. Therefore the distribution must be represented by a single term, and the variation with elevation must be exponential. This contradicts the observations. It is necessary to verify, of course, that the accuracy of the observations is sufficient to insure that the deviations from a purely exponential variation with elevation which are observed would result in a detectable change in the shape of the frequency distributions. Although such calculations are laborious, they are straightforward, and it is sufficient to state that they have been made. We therefore conclude that, at least at sea level, the electrons present are not the result of other electrons passing through the atmosphere from higher elevations, but some of them must have been produced

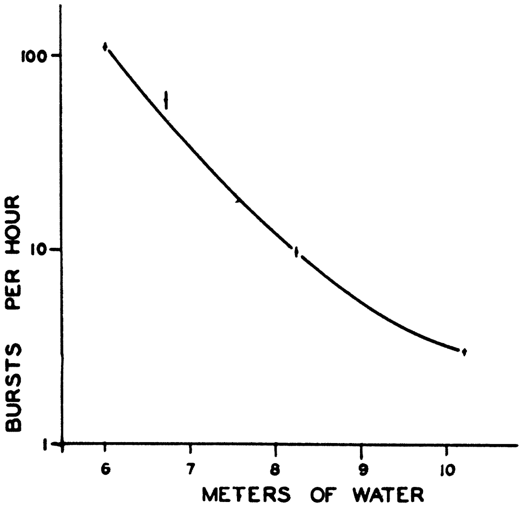

FIG. 2. The variation with elevation for large bursts from four cm of lead.

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[4] C. G. Montgomery and D. D. Montgomery, Phys. Rev. 47, 429 (1935).

[5] L. W. Nordheim, Phys. Rev. 51, 1110 (1937).

within the atmosphere below the altitude of Pike's Peak. Thus even up to a depth of six meters of water below the top of the atmosphere, we must add to the effects of the primary electron component the effects of electrons which have been produced in the atmosphere by processes other than those involved in the radiation of electrons and pair production by photons.

We are led to the same conclusion by the fact that large bursts are observed behind thick layers of lead. In this case, electrons falling upon the lead could not penetrate it unless their energies were unreasonably high. Here also it seems reasonable to invoke some mechanism for the production of electrons by the penetrating component of the cosmic radiation.

Electrons from the penetrating component

A penetrating component of the cosmic radiation which consists of mesotrons can produce electrons in at least two ways. First, a mesotron will occasionally eject an electron from an atom by such a close collision that the electron will have a large energy. The maximum energy that can be given to an electron by a mesotron in this way is limited by the principle of the conservation of momentum, but as the energy of the mesotron increases, the maximum energy transferable approaches the total energy. In fact, a 10^{10}-electron volt mesotron can give about half of its energy to an electron. Electron secondaries to the penetrating component arising in this way have been treated by Bhabha.[6] The second source of electrons is the spontaneous disintegration of mesotrons. This source is most effective in air and at low energies, but contributes appreciably to the number of high energy electrons. The effect of the instability of mesotrons on the absorption of cosmic radiation in air has been calculated by Euler and Heisenberg.[7] We wish to see how the behavior of the large bursts of ionization will be influenced by the inclusion of these two sources of electrons in the calculation.

A similar analysis has been already made by Euler[8] and Euler and Heisenberg,[7] and they have concluded that, in order to explain all the observations, it is necessary to invoke the existence of bursts caused directly by the penetrating component by a process of the explosion type. We find ourselves unable to agree with all their conclusions, chiefly because there is no direct evidence for the existence of appreciable numbers of showers of mesotrons, although they should have been observed, if present, in cloud chambers. Therefore, it seems to us to be worth while to see just how far it is possible to explain the behavior of large bursts without invoking any other processes than the ordinary multiplicative ones. Such a procedure may help clarify the situation and at least aid in stimulating discussion. We feel that neither point of view has a perfect case, but rather than attempt to discuss the merits of each in an impartial way, we shall adopt the more interesting and extreme position, and deny the existence of explosion showers until we are forced to recognize them.

THE FREQUENCY OF SHOWERS AND BURSTS

We can regard the frequency of occurrence of bursts containing more than N rays as the sum of four contributing factors, each of which is a function of the elevation, h, expressed as meters of water below the top of the atmosphere, and the number of rays, N. Thus:

$$R(h, N)=D(h, N)+C(h, N)+P(h, N)+Q(h, N), \quad (1)$$

D, C, P, and Q being the contributions from the disintegration electrons, the collision electrons, the primary electrons, and bursts from other causes such as explosions, respectively. We neglect Q. Now the number of bursts of a given size which will be produced by a given number of high energy electrons depends to a large extent on the magnitude of the fluctuations from the average behavior. An accurate expression for the fluctuations is not known at the present time. Although several investigators have estimated their magnitude, there seems to be no general agreement except that at thicknesses of material of the optimum or greater, the fluctuations are probably small. We shall therefore neglect them, except at small thicknesses, and remember that the calculations will be only approximate.

The number of disintegration electrons accompanying the mesotrons of the cosmic radiation

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[6] H. J. Bhabha, Proc. Roy. Soc. **A164**, 257 (1938).

[7] H. Euler and W. Heisenberg, Ergeb. der exakten Naturwiss. 17 (1938).

[8] H. Euler, Zeits. f. Physik **110**, 450, 692 (1938).

has been calculated by Euler and Heisenberg,[7] and we shall assume that a burst of N rays from the optimum thickness will be produced by an incident electron of energy $8NE_c$, where E_c is the critical radiation energy. For lead, E_c is 10^7 volts. If the number of mesotrons of momentum p or greater is taken to be

$$H(h, pc)=\left(\frac{2\times 10^9}{2\times 10^8 h+pc}\right)^\gamma \text{ per minute per cm}^2, \quad (2)$$

where pc is measured in electron volts, and γ is nearly 2, the number of disintegration electrons is

$$E(h, pc)=\frac{\mu c^2}{2pc}\frac{3}{4}\frac{X_0}{\tau c}\left(\frac{2\times 10^9}{2\times 10^8 h+2pc}\right)^\gamma, \quad (3)$$

where μ is the mass of the mesotron, τ the mean life, and X_0 the unit length of the cascade shower theory. If we choose μc^2 as 10^8 volts, $\tau=2.75\times 10^{-6}$ second, and $X_0=2.75\times 10^4(10/h)$ cm, then the number of bursts of more than N rays from the optimum thickness of material will be given by

$$D(h, N)=\frac{10^9}{64hNE_c}\left(\frac{2\times 10^9}{2\times 10^8 h+16NE_c}\right)^\gamma \text{ min.}^{-1}\text{ cm}^{-2}. \quad (4)$$

The number of bursts from collision electrons as calculated by Bhabha[6] is given to a rough approximation by Euler and Heisenberg as

$$C(h, N)=\frac{0.03}{N}\left(\frac{2\times 10^9}{2\times 10^8 h+8NE_c}\right)^\gamma. \quad (5)$$

Let us apply these expressions to the observations.

Bursts below sea level

The simplest case is that of observations made at large depths below sea level. The contributions of all terms except that of the collision electrons will be negligible, and we would expect the burst frequency to be proportional to the cosmic-ray intensity if $2\times 10^8 h$ is large compared to $8NE_c$, or $h \gg 40$ meters of water, for 100-ray showers from lead, since only the penetrating component is present and we can neglect disintegration except in air. Unfortunately, few observations are available, for example, those by Clay and by Weischedel,[8] but these agree with expectation in showing a burst frequency proportional to the cosmic radiation.

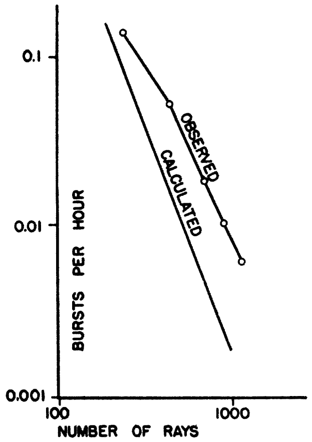

FIG. 3. Calculated and observed size-frequency distributions for large bursts from 11 cm of lead.

Bursts from thick lead shields at sea level

Behind lead shields thick enough so that showers initiated by electrons incident upon the lead are completely absorbed, the bursts are also produced solely by collision electrons. The observations made by Jesse and Doan[9] with a Carnegie Model C meter can be compared with the calculations. Fig. 3 shows the observed and calculated numbers of bursts per hour for a shield thickness of 11 cm of lead. The value of γ was taken as 1.87 as indicated by the observations of Ehmert.[10] The agreement of the two curves is surprisingly good when the uncertain nature of the calculations is considered. It should be noted that none of the constants involved were chosen to fit these particular observations. Probably the most serious uncertainty in the calculations is the lack of knowledge of the fluctuations. These are involved in the constant 0.03 in Eq. (5). The area of the chamber was used rather than the area of the lead, and probably a more correct value would be somewhat larger. The observed point at 230 rays is evidently too low since some bursts would be missed if the cosmic-ray record tended to be confused by the fluctuations in the background ionization. It is probably also true that 11 cm of lead is not quite enough to absorb completely all the showers produced by incident electrons. Thus it would seem unnecessary to invoke any additional processes to account for the observed number of bursts.

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[9] W. P. Jesse and R. L. Doan, Phys. Rev. **53**, 691 (1938).

[10] A. Ehmert, Zeits. f. Physik **106**, 751 (1937).

Bursts from thin lead shields at sea level

Behind thin lead shields at sea level, the electrons from the disintegration of the mesotrons should predominate in burst production. We have previously calculated[1] the number and the distribution in energy of the electrons which must be present at sea level to produce in 1.2 cm of lead the observed number of bursts and their size-frequency distribution. These calculations give the result that for bursts of the order of 100 rays, it is necessary to have electrons to the extent of about 0.5 percent of the total number of cosmic-ray particles having energies corresponding to values of pc between 10^9 and 10^{10} electron volts. These electrons have an energy distribution of the form B/E^s, where s is 2.6 for E equal to 10^9 volts, and s decreases slightly with increasing energy. Now we may calculate from Eqs. (2) and (3) the corresponding quantities, and we find that disintegration electrons amount to 0.75 percent of all the particles between 10^9 and 10^{10} volts. The parameter corresponding to s is 2.7 at 10^9 volts, but increases with increasing energy. The agreement, although not perfect, is satisfactory. Here again the uncertainty probably lies in the expression used for the fluctuations. We may, reversing the procedure, utilize the observations of the frequency of occurrence of large bursts to determine a value for the mean life of a mesotron, τ. Eq. (3) shows that the number of disintegration electrons is inversely proportional to the mean life. Hence we calculate that $\tau = 4.1 \times 10^{-6}$ sec., from the observed burst frequency. This value is in good agreement with those determined by other, quite independent methods.

Variation of burst frequency with elevation

To account for the number of bursts observed at sea level and below, it has been unnecessary to invoke any contribution of the high energy electrons from the primary electron component of the cosmic radiation. Indeed, the arguments presented may be taken as good evidence that such electrons do not penetrate to sea level in appreciable numbers. However, as we go to higher elevations it is necessary to consider effects of primary electrons. Unfortunately there is no way of measuring the number of high energy electrons in the atmosphere except by means of the large bursts which they produce. Thus we cannot derive the observed variation with elevation of large bursts from independent data, and we can only show that the observations are consistent among themselves. It is true that the latitude effect at high elevations tells us the energy distribution of primary electrons, but only for electrons with energies below about 2×10^{10} volts which can be bent by the earth's magnetic field. The primary electrons of interest to us have much higher energies at the top of the atmosphere. There are, however, three things which the burst observations should show. First, the initial rate of increase of bursts as we go above sea level should be quite small behind thick lead shields, since these bursts will vary with h as indicated by Eq. (5). Second, bursts from thin lead shields or shields of the optimum thickness should increase faster by a factor of $1/h$ as shown by (4). Third, at elevations of six meters of water, the effect of the primary electron component seems to predominate over the effects of the penetrating rays for both thick and 4-cm lead shields. However, as we go to lower elevations the effect of the primary electrons will die out sooner for thick shields than for shields of the optimum thickness. Hence we expect that the

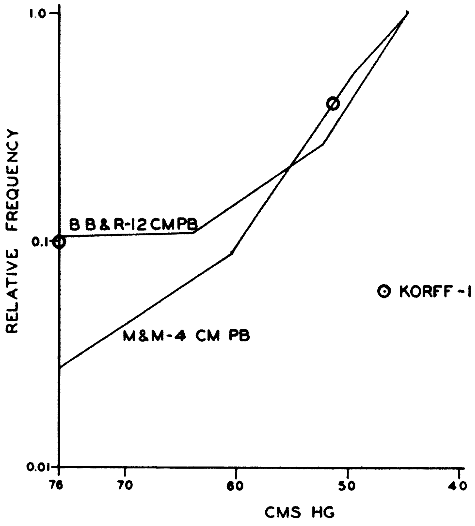

FIG. 4. The variation of burst frequency with elevation for bursts from the optimum thickness of lead (4 cm, reference 4) and from thick lead shields (R. D. Bennett, G. S. Brown, and H. A. Rahmel, Phys. Rev. **47**, 437 (1935); and S. A. Korff, Terr. Mag. and Atmos. Elec. **43**, 227 (1938)).

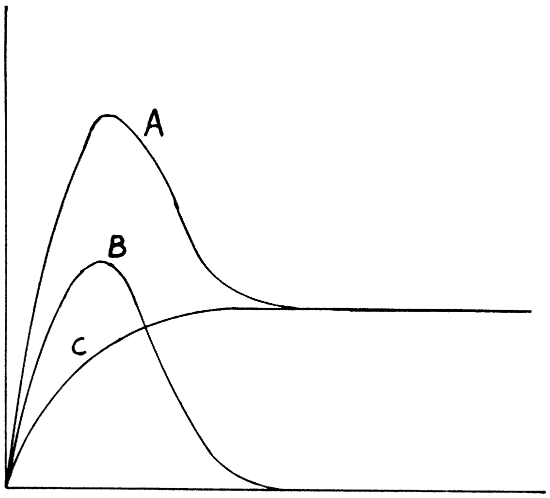

FIG. 5. The decomposition of a Rossi curve, A, into the portion caused by electrons, B, and the portion caused by the penetrating rays, C.

ratio of the number of bursts from thick lead at six meters to the number at sea level will be less than the corresponding ratio for bursts from four centimeters of lead. Fig. 4 shows some of the observations that have been made. It is evident that these three expectations are fulfilled. We could, of course, derive from the observations on the bursts the behavior of the high energy electrons produced by primary electrons. There is, however, too little observational material to warrant such a calculation at the present time.

A similar analysis to that just presented can be made for showers of small numbers of rays such as are measured by counter experiments. We shall not describe the analysis here, but it is evident that agreement between the observations and the results of such calculations is readily to be attained.

The shape of the Rossi curve

There is one more result of this analysis which is important to discuss since it leads us into difficulties. As shown in Fig. 5, the Rossi curve for sea-level observations (curve A) may be represented as the sum of two components: the contribution of disintegration electrons, curve B, and the contribution of the collision electrons, curve C. Now if we suppose that, at the optimum thickness, curve C is about $(1-1/e)$ of its value at large thicknesses, then we have from Eqs. (4) and (5) that the ratio of the number of showers at the maximum to the number at large thicknesses will be

$$r=\frac{10^9}{64E_c}\,\frac{100}{3h}\left(\frac{2\times 10^8h+8NE_c}{2\times 10^8h+16NE_c}\right)^{\gamma}+1-\frac{1}{e}.$$

For small showers we can neglect $16NE_c$ compared to 2×10^8h, and we calculate the values of r given in Table I. The calculated ratios for $N=200$ are also given in the table together with the observed values for comparison. It is evident that for small showers the agreement is good, and for 200-ray showers the agreement with the calculations is as good as the agreement between the different observers. We encounter no difficulty here, but find a further confirmation.

TABLE I. *Ratio of the number of bursts at the maximum of the Rossi curve to the number at large thicknesses.*

	SMALL SHOWERS Pb	SMALL SHOWERS Fe	200-RAY SHOWERS Pb	200-RAY SHOWERS Fe
Calculated	5.8	2.4	2.1	0.9
Observed	5.9[2]	2.7[2]	1.7[1] 2.8[3]	1.4[3]

[1] W. P. Jesse and R. L. Doan, Phys. Rev. **53**, 691 (1938).
[2] J. E. Moran and W. M. Nielsen, Phys. Rev. **52**, 564 (1937).
[3] H. Nie, Zeits. f. Physik **99**, 453 (1936).

DIFFICULTIES ENCOUNTERED IN THE PRESENT ANALYSIS

Although the shapes of the Rossi curves seem to be given correctly, we encounter a difficulty in the absolute number of large bursts from iron. From Eqs. (4) and (5), and taking account of the contribution of the collision electrons at the optimum thickness, it is possible to calculate the ratio of the number of showers observed from lead to the number from iron. The results of these calculations are given in Table II, together with the corresponding quantities derived from observation. The agreement is quite satisfactory for the case of the small showers, but the obser-

TABLE II. *The ratio of the number of showers from lead to the number from iron.**

	SMALL SHOWERS AT MAXIMUM	SMALL SHOWERS AT LARGE THICKNESSES	200-RAY SHOWERS AT MAXIMUM	200-RAY SHOWERS AT LARGE THICKNESSES
Calculated	2.5	1.0	13.8	7.7
Observed	1.8[2]	0.8[2]	1.2[3]	0.7[3]

* For references refer to previous table.

vations by H. Nie for the 200-ray showers are in marked disagreement with the calculation. Now it is just at this point that the difference between the present analysis and that of Euler[8] and Euler and Heisenberg[7] lies. The latter authors have interpreted Nie's data to mean that large showers from large thicknesses are produced by a new process, the explosion process first suggested by Heisenberg.[11] They have neglected the shower production by collision electrons at large thicknesses, which we have shown above to be sufficient to explain all the showers from lead. We shall not attempt to suggest a solution to the difficulty.

There is another phenomenon not explained by the present analysis which seems worth while to mention. At the Symposium last year we described some experiments, which we had made with an ionization chamber with very thin walls, on the showers from the atmosphere. The chamber was constructed of magnesium and had a diameter of 40 cm and a wall thickness of one centimeter. It was filled with nitrogen to a pressure of 14.6 atmospheres, and the ionization bursts were recorded photographically with a vacuum-tube electrometer. The number of bursts which could have come from the walls of the chamber and the wooden building in which the apparatus was housed was estimated by extrapolating to zero the curve relating the number of bursts to the thickness of magnesium over the chamber. Fig. 6 shows these observations. It is evident that the bursts observed with the chamber alone do not originate in the one centimeter wall. Now the magnitudes of these bursts correspond to showers of about a hundred rays, or to a density over the area of the chamber of about 800 per square meter. They occur with a frequency of one every 2.5 hours. Now it is quite difficult to conceive that showers produced in a material of so small a density as air by the cascade process would not spread to a much larger extent. Indeed, Auger[12] and his collaborators have observed such showers of large area as would be expected from the cascade process. It would not seem to be a case of fluctuations in density, since the bursts occur with a frequency at least comparable to the showers from one centimeter of lead, as is indicated by the point in Fig. 6. It seems more likely that these showers represent a large number of rays produced in a single act fairly close to the apparatus, and may, therefore, be of the nature of explosion showers.*

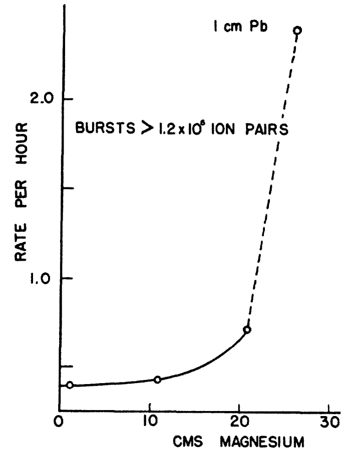

FIG. 6. Bursts from a magnesium chamber covered by various thicknesses of magnesium. The intercept of the curve on the axis of ordinates represents bursts from the atmosphere.

NUCLEAR VAPORIZATIONS

We wish to discuss now one other phenomenon which seems to be produced by the electrons and photons of high energy in the cosmic radiation, *viz:* the occurrence of groups of heavily ionizing particles which radiate outward from a center. Since they probably represent the disintegration of nuclei by the cosmic radiation, the term nuclear vaporization would seem to be a suitable one. These vaporizations have been observed by the use of two techniques: the Wilson cloud chamber[13] and photographic plates.[14] The heavily

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[11] W. Heisenberg, Zeits. f. Physik **101**, 533 (1936).

[12] P. Auger, R. Maze, P. Ehrenfest, A. Fréon, J. de phys. et rad. **10**, 39 (1939).

* *Note added in proof.*—Since the presentation of this paper, H. Euler and H. Wergeland have published [Naturwiss. **27**, 484 (1939)] the results of their calculations on the spreading of cascade showers in air. The nature of these results is such as to resolve the apparent discrepancy between the observations of Auger *et al.* and those described above, and it becomes unnecessary to invoke any mechanism of the explosion shower type. In fact by utilizing the cascade theory of spreading we have been able to calculate [Phys. Rev. **56**, 640 (1939)] from our observations the number and distribution in energy of the primary cosmic-ray electrons of the extremely high energies (of the order of 10^{15} electron volts) which are responsible for the production of these showers.

[13] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936); R. B. Brode, H. G. MacPherson, and M. A. Starr, Phys. Rev. **50**, 581 (1936).

[14] H. Wambacher, Zeits. f. tech. Physik **19**, 569 (1938).

ionizing particles represent protons which are pieces of the original nucleus which are boiled away when the energy of the cosmic ray is given to the nucleus. It has been maintained, and is still believed by some,[15] that the ionization produced in these vaporizations is responsible for the large bursts of ionization or Hoffmann *Stösse*. We have given considerable attention in the past[16] to this point, but we feel it would not be out of place to state again the three main lines of evidence which seem to indicate that *Stösse* are showers of electrons. First, in the high pressure ionization chambers in which the large bursts are usually observed, the recombination of the ions in a densely ionized track would be so large that it would require an unreasonably great number of protons to produce the amount of charge collected after a burst. Second, the observed probability that an arrangement of Geiger counters will be discharged simultaneously with the occurrence of a burst is just what would be expected if the particles which produced the bursts were electrons. Third, the size-frequency distribution of bursts is quite continuous from the small showers which are ordinarily measured by counter experiments to the largest bursts. In this connection, the data shown in Fig. 7 are interesting in that they represent observations, made with a single apparatus, of bursts corresponding in size to showers of from about 16 rays to 1600 rays (on the basis of a specific ionization in nitrogen of 33 ion pairs per cm). If the larger bursts were showers of heavily ionizing particles, we should expect some indication of this to be evident in the distribution curve.

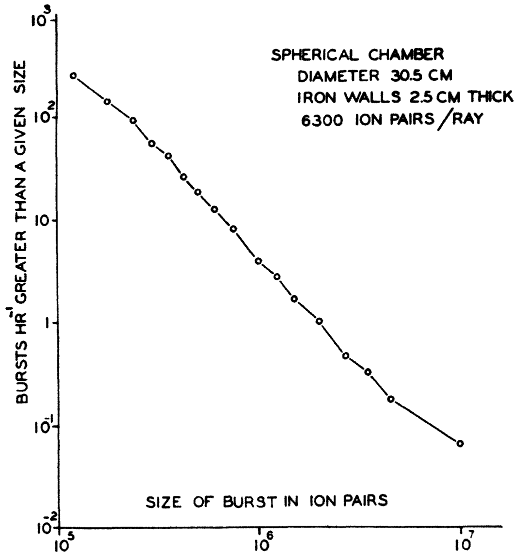

FIG. 7. Size-frequency distribution curve for bursts extending from about 16 to 1600 rays.

Variation with elevation of nuclear vaporizations

On the basis of the present ideas of nuclear structure we expect that besides the ionizing protons we would have an equal number of neutrons produced in a vaporization, which would not be detected in the cloud chamber. Several observers have demonstrated the presence of neutrons in the cosmic radiation, and it may well be supposed that they are produced in this kind of process. Dr. S. A. Korff has already described at this Symposium some measurements of the number of neutrons at very high elevations and discussed their consequences. From a consideration of observations made on mountain tops and at sea level it is possible to draw further conclusions. In Fig. 8 are shown Fünfer's observations[17] made with a proportional counter. On the same picture are shown the altitude variation of the large bursts from 4 cm of lead,[4] and the frequency of vaporizations observed by Anderson and Neddermeyer.[13] It is to be noted that these three phenomena all have the same increase with elevation, and can, therefore, be assumed to be produced by the same agency. We have shown that the behavior of the bursts is consistent with the idea that they are produced by electrons or photons of high energy, and we conclude that electrons or photons of high energy produce also the nuclear vaporizations and the neutrons. For the latter process, the photons are probably the more effective by the notorious factor, 137. These conclusions are further strengthened by the observation that quite frequently in the same cloud-chamber picture with a vaporization are electron tracks associated in time which we should expect to accompany a photon. Indeed, the first indications of neutrons in the cosmic radiation were photographs made

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[15] E.g., E. G. Steinke, discussion to reference 14.

[16] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **48**, 786 (1935).

[17] E. Fünfer, Zeits. f. Physik **111**, 351 (1938).

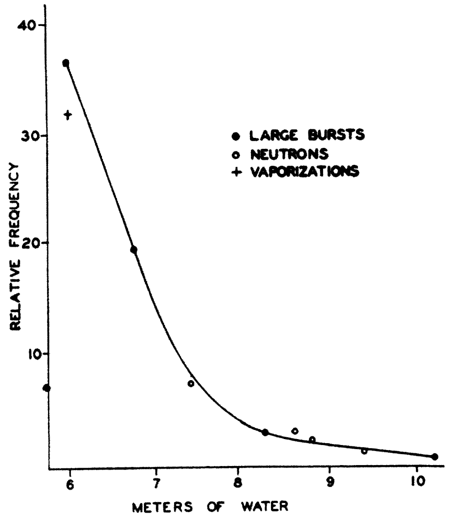

FIG. 8. The variation with elevation of neutrons, large bursts, and nuclear vaporizations.

by Locher[18] of showers of cosmic rays which contained objects which were interpreted as recoil tracks produced by collisions with neutrons.

The number of neutrons at sea level

We have recently[19] made an estimate of the number of neutrons of thermal energy which are present in the cosmic radiation at sea level. We employed an ionization chamber filled with boron-trifluoride gas at atmospheric pressure and measured the spurts of ionization produced by the alpha-particles ejected in the disintegration of the isotope of boron of mass ten. The number of alpha-particles from radioactive contamination in the chamber was determined by shielding the chamber with a thick layer of borax which absorbed all neutrons of thermal energy. Fig. 9 shows the distribution of the spurts of ionization from the alpha-particles, curve *A* being taken with the chamber shielded by borax and curve *B* with no shield. The difference between *B* and *A* represents the alpha-particles produced by neutrons. Curve *C* was taken with a 200 mg Ra-Be source of neutrons 15 meters away. Taking a cross section of 3×10^{-21} cm^2 for the $B^{10}(n-\alpha)Li^7$ reaction, the flux of neutrons of thermal energy was found to be 0.091 ± 0.007 per square centimeter per minute. This amounts to about one neutron for every 16 ionizing cosmic rays.

To show that nuclear vaporizations are responsible for the presence of this many neutrons, we should need some idea of the frequency of the nuclear process. Such data are unfortunately lacking. We can, however, make evident the degree of consistency of the observations which are at hand. The most likely process for the absorption of neutrons of thermal energy in air is the $N^{14}(n-p)C^{14}$ reaction. The cross section for the reaction[20] corresponds to an absorption coefficient of 4.8×10^{-4} cm^{-1} of standard air.* Now, in equilibrium, as many neutrons must be formed as disappear, and we must have 4.4×10^{-5} thermal energy neutron produced per cubic centimeter per minute. If no other process for neutron absorption is important, this must represent the total rate of neutron production of all energies.

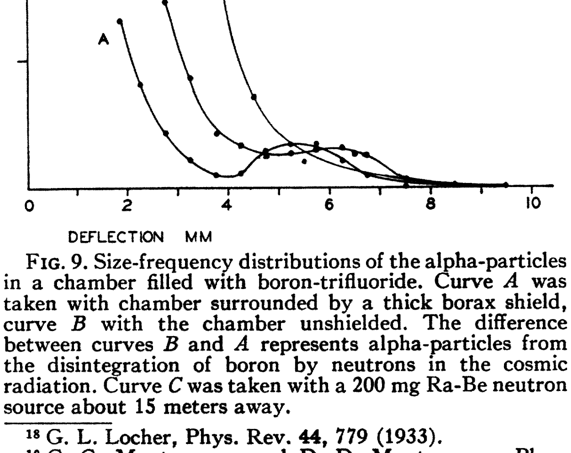

FIG. 9. Size-frequency distributions of the alpha-particles in a chamber filled with boron-trifluoride. Curve *A* was taken with chamber surrounded by a thick borax shield, curve *B* with the chamber unshielded. The difference between curves *B* and *A* represents alpha-particles from the disintegration of boron by neutrons in the cosmic radiation. Curve *C* was taken with a 200 mg Ra-Be neutron source about 15 meters away.

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[18] G. L. Locher, Phys. Rev. **44**, 779 (1933).

[19] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **56**, 10 (1939).

[20] J. R. Dunning, G. B. Pegram, G. A. Fink, D. P. Mitchell, Phys. Rev. **48**, 265 (1935).

* *Note added in proof.*—Another determination of the cross section for the $N^{14}(n-p)C^{14}$ reaction has been made by O. R. Frisch, H. v. Halban, and J. Koch [Nature **140**, 895 (1937)] which is considerably smaller. The value obtained corresponds to an absorption coefficient in standard air of 5.5×10^{-5} cm^{-1}. If we use this value the rate of production of neutrons by the cosmic radiation becomes 0.5×10^{-5} cc^{-1} min.$^{-1}$ and the neutron production cross section becomes 6×10^{-24} cm^2. The agreement in the rates of production of neutrons and protons by cosmic rays is equally good for either value of the absorption coefficient and probably both are within the limits of accuracy of the cloud-chamber determinations of the rate of proton production.

If we assume that at sea level about 1 percent of all the cosmic rays are high energy photons and effective in producing neutrons, we arrive at a cross section for the production of a neutron of about 5×10^{-23} cm^2, a value surprisingly high. The energy loss by neutron production is, however, probably negligible, since, if we take 10^7 electron volts as the energy loss per neutron, the mean energy loss per ray of all the cosmic rays is only 2×10^5 volts per meter of water equivalent. The protons resulting from the absorption of the neutrons of thermal energy have a range of only about a centimeter of air and will only be present to the extent of one for every 31,000 ionizing rays, a frequency of occurrence difficult, although not impossible, to detect in cloud chambers.

If we assume that all neutrons are produced in nuclear vaporizations, the number of protons produced should be equal to the number of neutrons. Anderson and Neddermeyer[15] estimate about 10^{-3} proton per cosmic ray at sea level. If we suppose that the protons have an average energy of 10^7 volts, their range will be 115 cm. Hence the rate of production of protons is about 1.5×10^{-5} per minute per cubic centimeter, in good accord with the rate of production of neutrons calculated above. Although these arguments cannot be regarded as proof that the nuclear vaporization process is the source of neutrons in the cosmic radiation, in the present state of our knowledge, the hypothesis does not appear unlikely.

Discussion

J. R. Oppenheimer, *University of California, California Institute of Technology:* The question has been raised here more than once of the relative frequency in different materials of large bursts. The maximum in the transition curve is very much more marked for heavy than for light materials: these bursts are presumably to be ascribed in large part to the multiplication of the soft radiation of air showers. Far beyond the transition maximum, where we must certainly have to do with bursts produced by the penetrating component, the frequency of large bursts is nearly independent of material, is if anything slightly higher in light materials than in lead. Especially Heisenberg has argued that this behavior so radically differs from what we should expect for multiplicative or cascade bursts that it must be construed as an argument in favor of a new mechanism of burst production, an explosion in which large numbers of particles are produced in an elementary process and to which further cascade multiplication adds only a little.

It would seem, however, that there are a number of points having to do with cascade theory and with the production of energetic secondary electrons by the penetrating component whose consideration tends to weaken this argument. It is these which we want here to consider.

Let us suppose then that the bursts under great thicknesses are initiated by the production of a high energy secondary (knock on) electron by a mesotron. Three factors will now influence the incidence of these bursts: the multiplication of a secondary of given energy; the probability that a mesotron of given energy will transfer energy to an electron; and the energy distributions of the mesotrons. For large bursts we are concerned with mesotrons of energy so high that their energy distribution may be taken to be just $dE/E^{\gamma+1}$ with $\gamma\sim1.8$–1.9, whereas for smaller showers the distribution may be taken nearly constant. The multiplication will proceed until the initial energy of the secondary is divided among particles of energy proportional to the critical energy I of the cascade theory. This energy is roughly that at which multiplication ceases, and is usually taken to be the energy at which ionization and radiation losses of an electron become equal, and thus inversely proportional to the atomic number Z. The bursts so produced will have a mean range (if we plot on a mass or better a Z scale) proportional to I. Essential now is the probability that a mesotron will transfer a given energy to a secondary electron. If we take for the cross section per electron the expression, surely valid for small energy transfers, dE/E^2, and extend it up to the