The Transition Effect for Large Bursts of Cosmic-Ray Ionization and the Number of Primary Electrons of Very High Energy

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Bursts of cosmic-ray ionization were observed in the open air and under heavy roofs, with and without a one-cm lead plate over the ionization chamber. The increase in the number of bursts in the presence of the lead under heavy roofs is interpreted as an increase in the number of rays in the showers from the roof, while in the open air the bursts from the lead probably originate to a large extent from the action of electrons of high energy which are not members of cascade showers starting at the top of the atmosphere. If the bursts from the atmosphere with no lead present are to be accounted for by the assumption that they are parts of extensive cascade showers, it is possible to derive the number and energy distribution of the primary cosmic-ray electrons of energies of the order of 2×10^{15} electron volts.

UNTIL recently, one of the most annoying and least well-understood aspects of cosmic-ray showers was the number of showers that were recorded even when great care was taken to remove all shower-producing material from the vicinity of the apparatus. The recent work of Auger[1] and his collaborators has done much to clarify our picture of the occurrence of showers from the air, and the situation is becoming more satisfactory. In making observations of showers or bursts of cosmic-ray ionization at depths below sea level, the effect of material surrounding the apparatus becomes more acutely felt, since it is impossible to avoid the presence of large quantities of dense matter at short distances in the walls and ceiling of the laboratory. To investigate these effects, we have made some observations on large bursts both in the open air and under thick roofs.

The ionization chamber and photographically-recording vacuum-tube electrometer that were employed have been previously described.[2] The chamber had a diameter of 40 cm, and was constructed of magnesium with walls one cm thick. If we choose 60 ion pairs per centimeter as the specific ionization of a ray in nitrogen, we calculate, making a correction for lack of saturation, 60 rays per million ion pairs collected. Observations were made at three stations in the Bartol Research Foundation Laboratory. The first was in a room covered with about a meter of earth, or beneath a mass of earth and air equal to 13.6 meters of water; the second was in a room with only a heavy ceiling of concrete over it, the equivalent depth being 11.1 meters; and the third was in a light wooden building at a depth of 10.2 meters. The ionization chamber was located about 1.5 meters from the ceilings of the rooms and was twice or more this distance from the walls. Observations were taken with and without a lead plate, 1 cm in thickness and 41 cm square, over the chamber. In Table I are given the results of these observations. The size-frequency distribution curves are plotted in Fig. 1.

Perhaps one of the first points to meet the eye in connection with these observations is the large number of bursts observed in the basement room under 13.6 meters of material, a number comparable with that observed in the open air at a depth more than three meters less. These bursts originate to a large extent in the overlying layer of earth. When the 1-cm lead plate is present over the chamber, the size of the burst from the earth is increased by the lead. This occurs because the radiation of electrons and pair production by photons continue to be important processes down to regions of lower energy in lead than in earth. This increase in size of a burst results in the occurrence of an increased number of bursts of a given size. All sizes of bursts appear to be multiplied in the same proportion, as is evident from the parallelism of the two distribution

[1] P. Auger, R. Maze, P. Ehrenfest, Jr., and A. Fréon, J. de phys. et rad. **10**, 39 (1939).
[2] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **47**, 429 (1935).

curves in Fig. 1, and we estimate this multiplication to be by about a factor of 1.7. The observed value of the multiplication may be compared with the value expected from the cascade theory. The average energy of a shower ray from a large thickness of earth is somewhat less than 10^8 electron volts. From the calculations of Arley,[3] we find, by interpolation, that an electron of 10^8 volts energy will be multiplied by a factor of 2.1 in a 1-cm lead plate. This is in sufficient agreement with the observed multiplication to assure us that the lead may be regarded as acting only to increase the number of rays in a burst, and is not acting as an appreciable source of additional showers.

If we try to interpret the observations made in the open air by the same picture, we encounter some difficulties. The frequency distributions with and without the lead are not parallel, but diverge considerably. If we interpret this as an increase in size of the bursts, we must conclude that the rays of a large burst have, on the average, a higher energy than those in a small burst. This is not in accord with the predictions of the cascade shower theory. We conclude, therefore, that at least two processes are taking place. First, a multiplication in the size of the air showers by the lead, just as in the case of the observations below ground, and second, the production of showers in the lead by some agency which differs from cascade electrons passing through the atmosphere. There is, however, another source of electrons which will produce large showers in the lead, namely, the electrons from the disintegration of cosmic-ray mesons. These electrons are not produced at the top of the atmosphere and are, therefore, not accompanied by a very large number of rays by the time that they reach sea level. Strictly speaking, this is also a process of multiplication of the number of electrons by the lead, and differs from the multiplication of showers from the earth only in the way the energy of the initial shower is distributed among the rays. We have shown elsewhere[4] that there is good agree-

[3] N. Arley, Proc. Roy. Soc. **A168**, 519 (1938).

[4] C. G. Montgomery and D. D. Montgomery, paper at the Chicago "Symposium on Cosmic Rays," June, 1939.

TABLE I. *The rate of occurrence of bursts of ionization per hour per 10^5 ion pairs, at three stations.*

Size in ion pairs $\times 10^{-6}$			1.1–1.2	1.2–1.3	1.3–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–4.0	4.0–6.0	$\geq$6.0
10.2 m depth	no Pb	Number of bursts	66	52	30	31	7	7	4	6	2
		Rate	0.19	0.15	0.035	0.014	0.003	0.003	0.0009	0.0007	0.005
	1 cm Pb	Number of bursts	165	137	137	124	41	21	30	9	12
		Rate	0.77	0.64	0.32	0.12	0.038	0.020	0.014	0.002	0.06
11.1 m depth	no Pb	Number of bursts	267	195	175	116	33	20	14	13	5
		Rate	3.52	1.20	0.54	0.14	0.041	0.025	0.009	0.004	0.03
	1 cm Pb	Number of bursts	722	318	536	497	184	81	80	53	33
		Rate	5.67	1.86	1.56	0.58	0.21	0.095	0.047	0.015	0.19
13.6 m depth	no Pb	Number of bursts	43	28	29	38	21	11	4	3	11
		Rate	0.54	0.22	0.11	0.060	0.033	0.017	0.003	0.002	0.09
	1 cm Pb	Number of bursts	85	70	128	113	61	35	33	16	19
		Rate	0.93	0.52	0.47	0.17	0.090	0.052	0.024	0.006	0.14

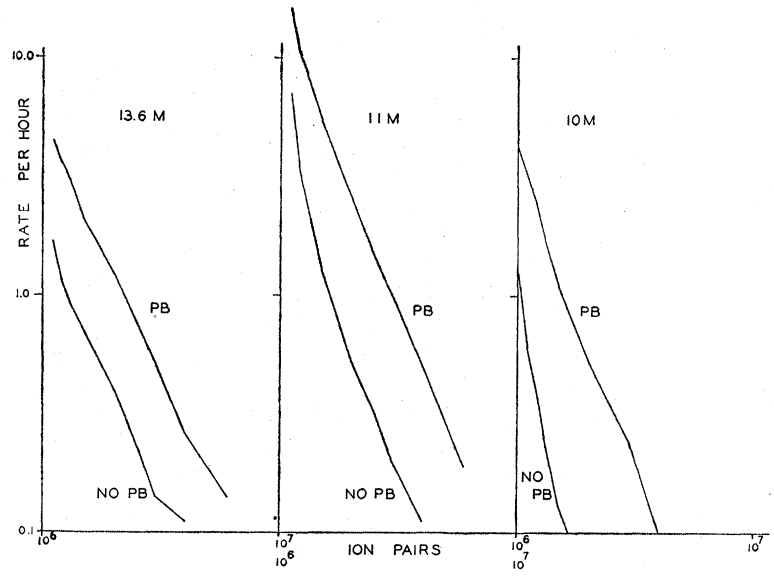

FIG. 1. The number of bursts of ionization greater than a given size, with and without a 1-cm lead plate over the chamber.

ment between the value of the mean life of a meson as calculated from the number of bursts observed and the values derived from absorption measurements of the cosmic radiation in air.

The set of observations made with the thick roof over the apparatus at a depth of 11.1 meters of water represents a case intermediate between the other two sets. We still have some divergence of the frequency distribution curves, but they are more nearly parallel than those taken in the open air.

We may draw some additional conclusions from the observations taken with no material over the chamber. If we suppose that the bursts observed are parts of showers of a great many rays which are spread over a large area, such as those observed by Auger,[1] and if we know the spreading to be expected, then we can calculate the number and distribution in energy of the primary electrons outside the earth's atmosphere which are responsible for these showers. The spreading to be expected has been estimated by Euler.[5] Let us suppose that a large shower of N rays at sea level has an axis passing through the point (r, φ) somewhere in the plane through the chamber perpendicular to the axis of the shower, not necessarily within the ionization chamber, supposed at the origin. Let $Np(r)$ be the average number of rays per unit area in the shower at the position of the chamber. Then if a is the area of the ionization chamber, the average number of rays in the chamber, n, is given by

$$n = aNp(r). \tag{1}$$

If this quantity is large, as in the case of these observations, we may neglect as a first approximation the fluctuations in it. If $j(E)dE$ be the number of primary electrons per square cm per second per unit solid angle having energies between E and $E+dE$, at the top of the atmosphere, then the number of showers coming from zenith angles between θ and $\theta+d\theta$, and having between N and $N+dN$ rays at sea level will be $j(E)\cdot(dE/dN)\cdot 2\pi \sin\theta dNd\theta$. The observed number of bursts, $O(n)$, having between n and $n+dn$ rays is

$$O(n)dn = \int_0^{\pi/2} d\theta \int_{r=0}^{\infty} 2\pi r dr \cdot j \cdot 2\pi \sin\theta \left(\frac{dE}{dN}\right) dN, \tag{2}$$

in which E is given as a function of N and θ by the cascade shower theory, and N is given as a function of n and r by relation (1). Since the air above sea level may be considered a large thickness, we may use an approximate form of the results of the cascade theory as given by Euler and Heisenberg,[6]

$$N = (E/E_c)^{1.44} e^{-0.73h/\cos\theta - 3.2}, \tag{3}$$

[5] H. Euler and H. Wergeland, Naturwiss. **27**, 484 (1939).

[6] H. Euler and W. Heisenberg, Ergebn. exakt. Naturwiss. **17**, 1 (1938).

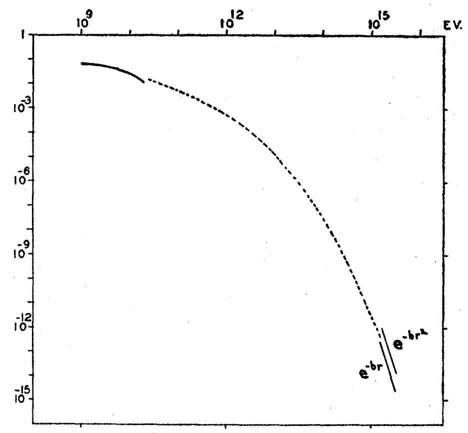

FIG. 2. The number of primary cosmic-ray electrons per square cm per second per unit solid angle having an energy greater than a given amount. The solid portion of the curve at low energies is derived from the latitude effect, the high energy portion is calculated from the burst observations in the open air.

where E_c is the critical energy for air, 1.5×10^8 electron volts, and h the atmospheric depth in meters of water. Let us assume that $j(E)$ may be expressed for the range of energies of interest to us by the empirical expression $j(E) = j_0/E^\lambda$, and we can evaluate the parameters j_0 and λ from the burst observations. The observations may be represented by an expression of the form $O(n) = A/n^s$. It is easy to show from (2) and (3) that $\lambda = 1.44(s-1)+1$. s appears to be about 5.6, and therefore $\lambda = 7.6$. From the number of bursts we can similarly evaluate j_0, if we know the function $p(r)$. Euler gives the function the form e^{-br}/r, where b is a constant. This form is evidently unsuited for application here on account of the infinity at the value r equals 0. We may, however, try similar functions of the types Ce^{-br} and Ce^{-br^2}, with the constants so determined that the functions are normalized and have the same "half-width" as Euler's function, the half-width being defined as the radius of the cylinder about the shower axis which contains one-half of the rays.* The results of these calculations may best be represented as in Fig. 2, where we have plotted on logarithmic scales the number of primary cosmic-ray electrons per square cm per second per unit solid angle having an energy greater than a given amount. The curve at the lower energies is determined by the latitude effect of the soft component of the radiation as calculated by Johnson.[7] The burst observations are concerned with the range of primary energies at about 2×10^{15} volts. Here, the two lines represent the two choices of the density distribution function. It is the uncertainty in the form of this function that limits the accuracy of the results of these calculations, but perhaps we can estimate from the figure the number of rays to better than an order of magnitude.

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* *Note added in proof.*—The correct function, $p(r)$, to choose is, of course, the average value of Euler's function taken over the area of the chamber. This function will have no singularity at the origin. The expression for this average value is somewhat unmanageable and was not employed for this reason. The showers which contribute most to the observed bursts will have their axes outside the chamber, and here the factor $1/r$ in Euler's expression is not very effective. We should therefore expect that a more accurate calculation will yield results closer to those resulting from the chosen form Ce^{-br} than from Ce^{-br^2}, although the more accurate value will lie between the two. It is obvious that a more accurate calculation would not alter the main conclusions of this section.

[7] T. H. Johnson, Rev. Mod. Phys. **10**, 193 (1938).