Burst Frequency as a Function of Energy

MARCEL SCHEIN AND PIARA S. GILL
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois

Size-frequency distributions of bursts were obtained from analyses of records made by Carnegie model C cosmic-ray meters, shielded by 12 cm of lead, stationed at different locations. The number of particles per burst ranged from 200 to 10,000. Assuming that the number of particles in a given burst is proportional to the energy of the incident ray, energy distribution curves for the burst-producing radiation were made and compared with the depth-ionization curve obtained underground by Wilson. Because both curves have nearly the same shape, it was concluded that at least the greater part of the burst-producing radiation at sea level consists of penetrating ionizing rays, presumably mesotrons. The value of 10^{-4} was found for the creation probability of a burst by a mesotron of about 2×10^{10} ev energy in a thickness of 12 cm of lead. This leads to a cross section per nuclear particle (proton, neutron) of 2×10^{-30} cm^2, which value is independent of the energy of the incident particle. The ratio of the burst rates at Huancayo (3350 m elevation above sea level) and Cheltenham (72 m elevation) for different burst magnitudes was found to be constant, within the statistical errors, up to energies of about 1×10^{11} ev, and likewise for Teoloyucan (2285 m elevation) and Cheltenham. For energies higher than 10^{11} ev, the corresponding ratios of the burst rates at the high to those at the low altitudes increase rapidly with increasing energy of the burst. In order to account for this effect, it is assumed that some of the largest bursts are created by photons or electrons of energies greater than 10^{11} ev, a part which becomes predominant at higher elevations. This suggests a possible mechanism for the creation of mesotrons by the soft component of cosmic radiation in the earth's atmosphere.

INTRODUCTION

THE purpose of the present paper is to give more information about the general properties and the energy distribution of the burst-producing radiation responsible for bursts in great thicknesses of lead.

Data for a long period of time were available from records made with five of the Carnegie model C cosmic-ray meters.[1] Table I gives the location, the geomagnetic latitude, the elevation above sea level, and the normal barometer for four of these meters located at permanent stations. Records of the bursts were also obtained from the cosmic-ray meter on the *R.M.S. Aorangi* during the several voyages between Vancouver, B. C., and Sydney, N. S. W.

The ionization chamber where the bursts occur consists of a steel bomb of 19.3 liters volume. Each of these chambers is filled with very pure argon at a pressure of 50 atmospheres except the one in Teoloyucan, Mexico, in which the pressure is 40 atmospheres. The shielding of each meter is equivalent to 12 cm of pure lead, which is sufficient to stop all showers and shower-producing radiation.

A change in the position of the electrometer needle as registered on a photographic film must be due to one or more of the following processes: (1) Accidental deflections, (2) statistical fluctuations of the ionization, (3) time variations in the cosmic-ray intensity, and (4) bursts. Such instrumental failures as a loose electrical contact may make the position of the needle erratic. The resulting deflections should, however, always be positive if they are caused by sudden ionization, whereas such instrumental difficulties, which are rare, introduce equally frequent deflections in the positive and negative directions, and are readily recognizable. While (3) causes only slow variations in the position of the electrometer needle, (2) and (4) give, from time to time, sudden changes easily distinguishable from the other type of variations. It is, however, important to establish exact criteria for distinguishing bursts from statistical fluctuations.

TABLE I. *Location, elevation, and geomagnetic latitude of cosmic-ray stations.*

Station	Geomagnetic Latitude	Elevation above Sea Level	Normal Barometer
Cheltenham (U. S. A.)	50.1 N	72 m	760 mm
Teoloyucan (Mexico)	29.7 N	2285 m	585 mm
Huancayo (Peru)	0.6 S	3350 m	515 mm
Christchurch (New Zealand)	48.0 S	8 m	760 mm

[1] A. H. Compton, E. O. Wollan and R. D. Bennett, Rev. Sci. Inst. 5, 415 (1934).

Bennett, Brown and Rahmel[2] carried out calculations of this kind for a Carnegie model C cosmic-ray meter and obtained the following results: at Chicago a statistical fluctuation corresponding to 0.5 mm deflection of the electrometer needle is found to occur, on the average, once every 42.2 hours, and for 0.75 mm deflection, once every 18,000 hours. Actually observed were 6–8 bursts between 0.5 and 0.75 mm deflection per 42.2-hour period, so only bursts less than 0.5 mm should be omitted.

[2] R. D. Bennett, G. S. Brown and A. H. Rahmel, Phys. Rev. **47**, 437 (1935). These authors have also discussed in detail possibility that the registered sudden deflections may result from such an origin as ionization by collision. (Cf. R. D. Bennett, Phys. Rev. **45**, 491 (1934).)

The Size *vs.* Frequency Distribution of Bursts

To get the size *vs.* frequency distribution, the bursts were classified according to size, and the number of bursts in each such group was counted. Bursts of size 1 are those which correspond to an electrometer deflection between 0.5 mm and 1.5 mm; of size 2, to a deflection between 1.5 mm and 2.5 mm; etc.

In Table II the number of bursts registered in each size range is given, and below it, in parentheses, the rate of occurrence in bursts per day. The actual number of days used in the count is given below the location. These figures show that the frequency of bursts decreases very rapidly with increasing size; hence for very large

TABLE II. *Total number of bursts for given sizes as well as the average number of bursts per day at four different cosmic-ray stations.*

Size	Cheltenham (281 days)	Teoloyucan (563 days)	Huancayo (500 days)	Christchurch (566 days)
1	821 (2.92±0.062)	2650 (4.7±0.07)	3697 (7.39±0.08)	1220 (2.15±0.04)
2	292 (1.04±0.04)	1190 (2.1±0.04)	1555 (3.11±0.05)	426 (0.75±0.025)
3	116 (0.41±0.026)	316 (0.56±0.02)	606 (1.21±0.03)	129 (0.23±0.014)
4	57 (0.20±0.02)	150 (0.27±0.014)	284 (0.57±0.02)	56 (0.099±0.009)
5	30 (0.107±0.013)	60 (0.107±0.009)	145 (0.29±0.016)	24 (0.04±0.005)
6	16 (0.06±0.01)	56 (0.099±0.009)	74 (0.15±0.012)	13 (0.023±0.003)
7	13 (0.046±0.009)	19 (0.03±0.005)	50 (0.10±0.010)	4 (0.007±0.002)
8	7 (0.025±0.006)	16 (0.028±0.005)	51 (0.10±0.009)	2 (0.004±0.002)
9	5 (0.018±0.005)	16 (0.028±0.005)	30 (0.06±0.007)	3 (0.005±0.002)
10	3 (0.01±0.004)	6 (0.011±0.004)	19 (0.038±0.006)	3 (0.005±0.002)
11	3 (0.01)	7 (0.012)	16 (0.032±0.005)	2 (0.004)
12		3 (0.005)	17 (0.034±0.006)	1 (0.002)
13	1 (0.004)	4 (0.007)	7 (0.014±0.004)	4 (0.007)
14		6 (0.011)	6 (0.012±0.003)	1 (0.002)
15	1 (0.004)	3 (0.005)	2 (0.004±0.002)	1 (0.002)
16		2 (0.004)	3 (0.006±0.002)	2 (0.004)
17		2 (0.004)	5 (0.010±0.003)	
18	1 (0.004)	2 (0.004)	4 (0.008±0.003)	1 (0.004)
19			3 (0.006±0.002)	1 (0.004)
20			3 (0.006±0.002)	

bursts the statistical errors become very considerable. For instance, a burst of size 18 occurred only twice at Teoloyucan in the whole period of 563 days. All discussions given later in this paper concerning the distribution curves of bursts deal only with sizes up to 10.

Size-frequency distribution curves obtained with seven different model C cosmic-ray meters, for bursts of sizes 1 to 5, have been published by Doan.[3] In this smaller range he proposed the simple exponential, $F=F_0e^{-as}$, where F represents the frequency, s the size, and F_0 and a are empirical constants, as giving a satisfactory representation of the data. In Fig. 1 the logarithm of the average number of bursts per day (log F), from Table II, is plotted against the size of bursts. The curves represent the results for Cheltenham, Teoloyucan, Huancayo and Christchurch, respectively. All four curves show definitely that the size-frequency distribution cannot be represented by a simple exponential function. Doan's straight lines represent, however, as good approximations to the first portions of our curves as can be expected in view of the smaller number of bursts that he had for study.

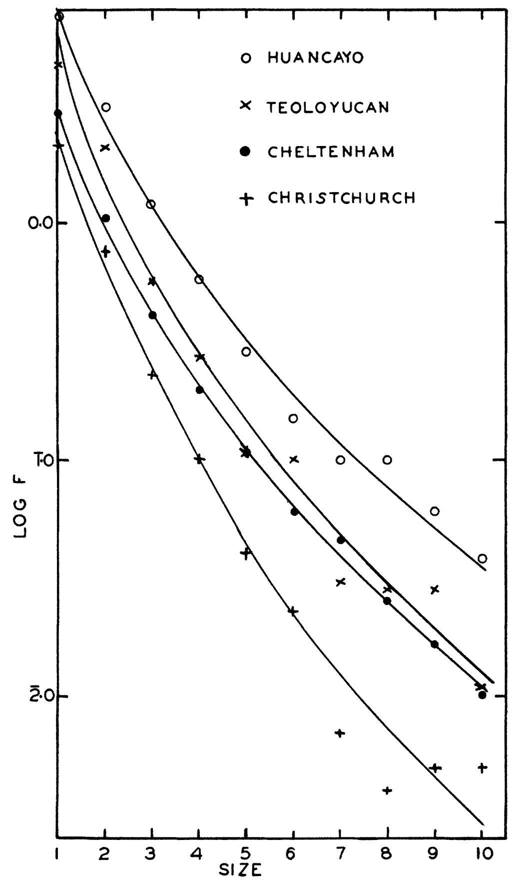

FIG. 1. Size-frequency distribution of bursts at Huancayo, Teoloyucan, Cheltenham and Christchurch.

ENERGY DISTRIBUTION OF THE BURST-PRODUCING RADIATION

The dependence of the frequency of occurrence upon the size of the bursts (Table II) can be used for determining the energy distribution of the burst-producing radiation. For this purpose one has first to calculate the number of particles traversing the chamber for a burst of a certain size. This is possible on the assumptions that every burst particle forms the same average number of ions per cm of path and that the mean paths of the particles in the ionization chamber are equal.

The total number of ions M corresponding to an electrometer deflection α in mm is given by the expression,

$$M=\frac{C\alpha}{S}\times\frac{1}{300}\times\frac{1}{4.78\times10^{-10}},$$

where C represents the capacity, and S the sensitivity of the electrometer. The value of S varies by only a few percent, and in calculating M we use its mean value. In Table III, C, S, and values of M, calculated for $\alpha=1$, are given for the four meters.*

To find the number of rays present in a burst of size 1, we have to divide M_1 by the number of ions, m, produced along the path of each burst ray. To obtain this number, we multiply Swann's[4] value of 60 ions per cm path in standard air by 67, the ratio of the ionization in very pure argon at 50 atmospheres to that in standard air. As the mean path, l, of a burst ray in a spherical chamber of radius r is $l=(4/3)r=24$ cm,

[3] R. L. Doan, Phys. Rev. **49**, 107 (1935).

* Because of the fact that during the period of observation the pressure in the cosmic-ray meter stationed at Christchurch did not stay constant, which makes the calculation of the number of burst particles involved in a burst of a certain size highly uncertain, for all further discussions the Christchurch data are omitted.

[4] W. F. G. Swann, Phys. Rev. **44**, 961 (1933).

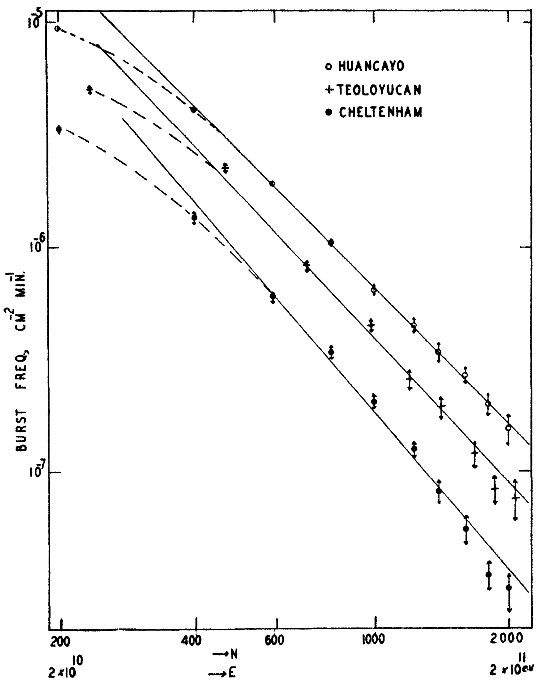

FIG. 2. Energy distribution curve of the burst-producing radiation at Huancayo, Teoloyucan and Cheltenham.

the number of ions formed along the path of one burst particle is given by: $m=60\times 24\times 67=96{,}000$ ions per ray. From this we obtain the number, N_1, of rays present in a burst of size 1, $N_1=M_1/m$. In Table III, N_1 is given for the different meters.

Furthermore, we suppose that the number of particles, N, present in a burst is proportional to the energy, E, of the burst-producing radiation. Hence, we obtain $E=E_r\times N$, where E_r is the average energy per ray. An approximate value of E_r can be determined from the mean range of the burst particles measured in lead and iron by two different methods. The transition curve leads to a value of about 4.5 cm of lead and 10 cm of iron,[5, 6] whereas Nie[7] gets a value of 5 cm of lead from measurements with a double chamber and absorber between the chambers. The range of about 5 cm of lead is considerably larger than that for ordinary shower particles, which is approximately 1.7 cm of lead. In order to penetrate a thickness of 5 cm of lead, electrons must have very high energies ($E\gg 10^9$ ev), which seems highly improbable considering the fact that we are dealing with secondary burst particles. On the other hand, if we assume that at least the majority of burst rays are mesotrons, we find, from ionization loss measurements,[8] the mean energy of a burst particle to be 10^8 ev. Euler and Heisenberg[6] estimated the same value. If we assume that the value of $E_r=10^8$ ev is roughly correct, we are able to calculate for bursts of given sizes the corresponding energies of the burst-producing rays. In Table III, E_1 represents the energy corresponding to size 1 for each different meter. It is interesting to notice that the largest of all registered bursts which occurred at Huancayo was of size 50 and consisted of about 10,000 particles. From our estimate, the energy corre-

TABLE III. *Dependence of size of burst on frequency. C is the capacity; S is the sensitivity of the electrometer; M_1 is the number of ions; N_1 is the number of rays in burst of size 1; and E_1 represents the energy corresponding to size 1 for each meter.*

	CHELTENHAM	TEOLOYUCAN	HUANCAYO	R.M.S. AORANGI
C (cm)	65.0	64.5	67.2	60.0
S (div./volt)	24.0	25.0	24.0	15.0
M_1 (ions)	1.9×10^7	1.8×10^7	1.9×10^7	2.8×10^7
N_1	200	235	200	300
E_1 (ev)	2×10^{10}	2.4×10^{10}	2×10^{10}	3×10^{10}

TABLE IV. *Number of bursts per cm² per second for given sizes at Cheltenham, Teoloyucan, and Huancayo.*

SIZE S	CHELTENHAM $E_1=2\times 10^{10}$ EV	TEOLOYUCAN $E_1=2.4\times 10^{10}$ EV	HUANCAYO $E_1=2\times 10^{10}$ EV
1	3.4×10^{-6}	5.1×10^{-6}	7.6×10^{-6}
2	1.36×10^{-7}	2.3×10^{-6}	3.4×10^{-6}
3	6.3×10^{-7}	8.4×10^{-7}	1.6×10^{-6}
4	3.4×10^{-7}	4.5×10^{-7}	8.3×10^{-7}
5	2.0×10^{-7}	2.6×10^{-7}	4.9×10^{-7}
6	1.3×10^{-7}	1.9×10^{-7}	3.3×10^{-7}
7	8.4×10^{-8}	1.2×10^{-7}	2.6×10^{-7}
8	5.6×10^{-8}	8.4×10^{-8}	1.8×10^{-7}
9	3.5×10^{-8}	7.7×10^{-8}	1.3×10^{-7}
10	2.8×10^{-8}	5.6×10^{-8}	9.1×10^{-8}
11	1.4×10^{-8}	4.9×10^{-8}	5.6×10^{-8}
12	7.0×10^{-9}	4.2×10^{-8}	4.9×10^{-8}
13	7.0×10^{-9}	3.5×10^{-8}	2.1×10^{-8}
14	7.0×10^{-9}	2.8×10^{-8}	1.4×10^{-8}
15	7.0×10^{-9}	2.1×10^{-8}	1.4×10^{-8}
16	7.0×10^{-9}	2.1×10^{-8}	1.4×10^{-8}
17	7.0×10^{-9}	1.4×10^{-8}	1.4×10^{-8}
18	7.0×10^{-9}	1.4×10^{-8}	7.0×10^{-9}
19	2.8×10^{-9}	1.4×10^{-8}	7.0×10^{-9}
20	2.8×10^{-9}	1.4×10^{-8}	

[5] W. P. Jesse and R. L. Doan, Phys. Rev. **53**, 691 (1938).
[6] H. Euler and W. Heisenberg, Ergeb. exakt. Naturwiss. **17**, 1–70 (1938).
[7] H. Nie, Zeits. f. Physik **99**, 776 (1936).
[8] P. Ehrenfest, Comptes rendus **207**, 573 (1938).

sponding to a burst of this size would be 10^{12} ev. There are very rare cases of still larger bursts which threw the electrometer needle off scale.

This value of $E=NE_r$ is to be considered as only a rough approximation. For, on the one hand, not all of the high energy burst particles will ordinarily traverse the chamber. Some may go in other directions, and some may be absorbed before reaching the gas in the chamber. On the other hand, a certain number of secondary electrons will always be present, whose energy will probably average less than 10^8 ev. The errors thus introduced, however, can presumably be corrected by introducing a multiplying factor independent of E, which will not differ greatly from unity. Thus this approximation should not affect our consideration of the shape of the number *vs.* energy curves.

Knowing the energies of the burst-producing cosmic-ray particles, we can introduce them into the size-frequency relation of Table II, using for each burst size the corresponding energy value E. To reduce the statistical errors, we have calculated the so-called cumulative energy-distribution curves, considering for a certain energy E of the burst-producing radiation the frequency of occurrence of all the bursts having energies greater than E. Thus the first point in the cumulative distribution function represents all of the bursts registered by one of the cosmic-ray meters, the second point gives all the bursts except those of size 1, the third point, all of the bursts except those of sizes 1 and 2, and so on. A great advantage of these cumulative energy distribution curves is that they can be compared directly with the experimental data obtained from intensity measurements at great depths. In Table IV are given the values of the frequency of occurrence of bursts having energies greater than E per cm^2 of the chamber per minute, where $E=sE_1$.

In Fig. 2, the values of Table IV are represented in a double logarithmic diagram, where the abscissa represents the number of burst particles directly proportional to the energy of the burst-producing radiation. Burst frequencies corresponding to an energy greater than 2.5×10^{11} ev are omitted because their statistical errors are too great. This is shown in Fig. 3 where all of the points up to an energy of 4×10^{11} ev (4000

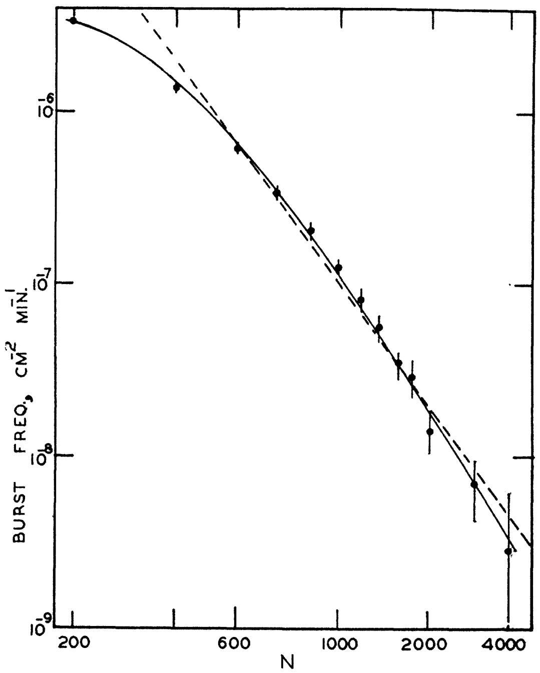

FIG. 3. Frequency *vs.* N (number of burst particles) at Cheltenham.

burst particles) are given for Cheltenham. The standard errors of the first 10 points in the curve run from 2 to about 10 percent. The position of the first point on each curve of Fig. 2 is considerably uncertain. This is due to the fact that part of the smallest bursts (size 0.5 mm) was apparently missed for experimental reasons. Omitting the first points, we tried to fit straight lines through the experimental points of Fig. 2 and also Fig. 3.

As shown in Fig. 2, the differences in elevation and geomagnetic latitude have no appreciable influence on the shape of the energy distribution curves for the burst-producing radiation. On the other hand, the corresponding absolute values of the burst frequency for different meters differ distinctly from each other. Comparison of the curve from Cheltenham with those from Teoloyucan and Huancayo shows that the difference is apparently due to the differences in geomagnetic latitude and elevation.

Jesse and Doan[5] have published size-frequency distribution curves using different thicknesses of lead shielding for the ionization chamber. The burst frequencies given by them for shields of 10.7 cm of lead are comparable with our results. Fig. 4 shows a comparison of their data, when reduced in the same manner as ours, with the curve (solid line) representing our Cheltenham data. In view of the relatively large statistical errors, it will be seen that the agreement in both absolute frequency and shape of curve is quite satisfactory.

A similar comparison with burst data recently published by Korff,[9] who used a chamber of 15 cm diameter shielded by 11 cm of lead, when analyzed by the same method, shows about the same total frequency of bursts of all energies, but a relatively smaller number in his chamber at the higher energies. This is shown in the broken line of Fig. 4. In spite of the relatively small number of bursts studied by Korff (a total of 709 of all sizes), the difference would seem to be statistically significant. It is conceivable that with his smaller chamber, recombination of ions would be a more significant factor in reducing the apparent size of the larger bursts.

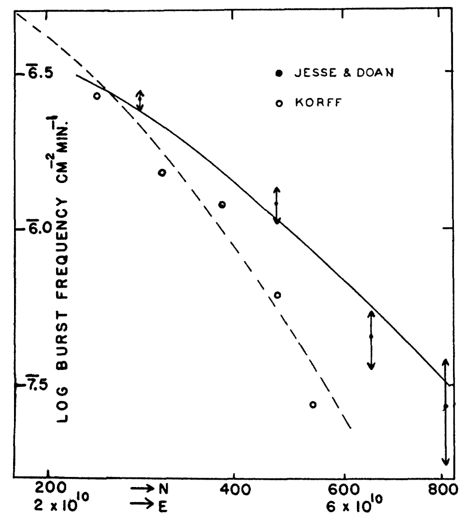

FIG. 4. Energy distribution curve of the burst-producing radiation at Cheltenham compared with the data obtained by other investigators.

SIGNIFICANCE OF THE ENERGY DISTRIBUTION CURVE

It has been pointed out by different investigators[10] that the energy distribution of the primary cosmic radiation can be represented by a simple power law of the form: $f(E)=AE^{-\gamma}$, where $f(E)$ represents the number of cosmic-ray particles having energies greater than E, and A and γ are empirical constants. An energy spectrum of this kind is represented by a straight line on a double logarithmic diagram such as Fig. 2, the negative slope of the line being equal to γ. The accurate determination of the value of γ is of great interest because it is closely related to many cosmic-ray phenomena. Johnson,[11] using the high altitude measurements of Bowen, Millikan and Neher,[12] calculated an approximate value of $\gamma=1.8$. However, this calculation is concerned only with the energy interval which is given by the latitude effect and which lies between about 2×10^9 and 1.5×10^{10} ev. For energies greater than 10^{10} ev, Wilson's,[13] Ehmert's,[14] and Clay and von Gemert's[15] depth-intensity curves give a value of γ which changes between the limits $1.7<\gamma<2.5$. This would be not inconsistent with the assumption that the energy spectrum of the primary radiation at the top of the atmosphere can be represented by a power law with a value of γ in the neighborhood of 2.

It was pointed out earlier in the paper that the energy distribution curves for the burst-producing radiation given in Fig. 2 can be represented in first approximation by straight lines in a double logarithmic diagram. This means that, if the formula $f(E)=AE^{-\gamma}$ is applied to the burst-producing radiation, the value of γ is nearly constant over the energy range from 2×10^{10} to 2×10^{11} ev. The values of γ are *2.0*, *2.1*, and *2.3* for Huancayo, Teoloyucan and Cheltenham, respectively.[16]

In investigating the nature of the burst-producing radiation, let us compare the energy spectrum of the burst-producing radiation with the depth-intensity curve obtained by Wilson.[13] It has been recently shown[17] that most, if not

[9] S. A. Korff, Terr. Mag. **43**, 227 (1938).
[10] L. W. Nordheim, Phys. Rev. **53**, 694 (1938); W. Heitler, Proc. Roy. Soc. **A161**, 261 (1937).
[11] T. H. Johnson, Phys. Rev. **53**, 499 (1938).
[12] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **52**, 80 (1937).
[13] V. C. Wilson, Phys. Rev. **53**, 337 (1938).
[14] A. Ehmert, Zeits. f. Physik **106**, 751 (1937).
[15] J. Clay and A. von Gemert, Physica **VI**, 497 (1939).
[16] In a recent publication A. Sittkus [Zeits. f. Physik **112**, 626 (1939)] gave the value of $\gamma=1.9_2$ for bursts produced in a thickness of 4 cm of lead.
[17] V. C. Wilson, Phys. Rev. **55**, 6 (1939).

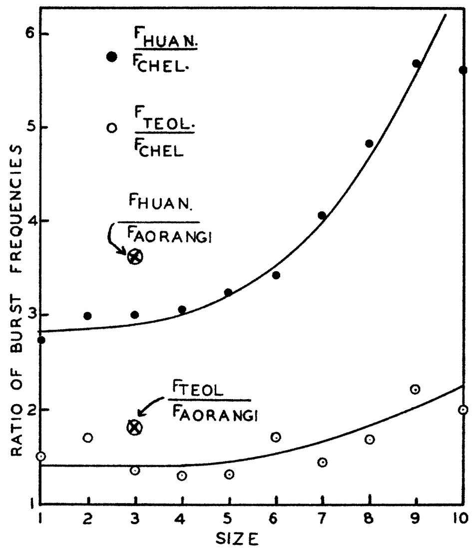

FIG. 5. Altitude dependence of the frequency of occurrence of large bursts produced in 12 cm of lead.

all, of the cosmic rays at great depths are ionizing particles (mesotrons). As we suppose that in dense materials mesotrons lose their energy primarily by ionization (other kinds of absorption effects are probably small in comparison with the ionization loss), we are able to estimate the approximate energies of the cosmic-ray particles which penetrate to a certain depth. Each point in Wilson's depth-intensity curve gives the total number of vertically incident cosmic-ray particles having energies greater than the threshold value E required for the penetration to the corresponding depth. Thus Wilson's curve should represent the energy distribution of high energy cosmic-ray particles at the surface of the ground, and should be directly comparable with the energy spectrum of the burst-producing radiation at sea level.* We find that in the energy range between 2×10^{10} and 2×10^{11} ev, γ has the mean value of 2.1 in Wilson's depth-intensity curve. This has to be compared with the corresponding value of $\gamma=2.3$ at Cheltenham. The close agreement between these two curves strongly suggests that both represent energy spectra of the same kind of ray. If, then, the deeply penetrating rays consist of ionizing particles, presumably mesotrons, we may assume the burst-producing rays to be particles of the same kind.

THE CROSS SECTION FOR BURST-PRODUCTION

The relation between the depth-intensity curve of cosmic rays under ground and the energy distribution of the burst-producing radiation indicates a possibility of estimating an approximate value of the cross section for the creation of a burst. The values obtained in Table IV give the burst frequencies, f_B (at Cheltenham), corresponding to certain threshold energies E. On the other hand, from Wilson's depth-intensity curve one can compute the number of penetrating particles at sea level n_P corresponding to the same energies E. Thereby: $W=f_B/n_P$ represents the probability of the creation of a burst of given size in a thickness of 12 cm of lead by penetrating particles of the same energies. The comparison between the two curves in Fig. 5 indicates that f_B/n_P is nearly independent of the energy of the incident rays for the interval $2\times 10^{10}<E<2\times 10^{11}$ ev. Hence the value of n_P has to be determined for only one of the threshold energies.

This was done in the following way. The number of fourfold coincidences per cm² per minute at a depth of 80 m water equivalent below sea level, where $E=2\times 10^{10}$ ev, is given by Wilson[17] as 3.8×10^{-3}. Wilson's counter telescope registered rays within a solid angle of about 29 degrees. Using the $\cos^2 Z$ law for the intensity distribution of cosmic rays with zenith angle Z, we obtain 7 : 1 for the ratio of the total penetrating radiation incident from all directions to that within a solid angle of 29 degrees. Therefore, the number of penetrating particles incident from all directions at the depth of 80 m water equivalent is equal to $7\times 3.8\times 10^{-3}=2.7\times 10^{-2}$. Under the assumptions made in the last section, this value should represent the total number, n_P, of mesotrons per cm² per minute at sea level having energies greater than $E>2\times 10^{10}$ ev.

Using this value of n_P, we obtain for the probability of burst-production by mesotrons

* In making this statement, and in what follows, we ignore the slight difference resulting from the fact that in Wilson's experiments only rays of nearly vertical incidence are used, whereas the bursts result from rays in all directions.

the value:

$$W=\frac{3.4\times 10^{-6}}{2.7\times 10^{-2}}=1.3\times 10^{-4}.$$

This means that, in a thickness of 12 cm of lead, only one burst with more than 200 particles occurs, on the average, for 7500 incident mesotrons. The number of atoms (nuclei) in 1 cm^3 of lead is equal to 3.4×10^{22} and hence the cross section for burst-production per one lead nucleus is given by:

$$\Phi_{\mathrm{Pb}}\approx\tfrac{1}{3}\times 10^{-27}\ \mathrm{cm}^2.$$

Calling A_{Pb} the atomic weight of lead, we obtain the corresponding cross section per nuclear particle (proton or neutron):

$$\Phi_{\mathrm{Pb}}\approx\frac{1}{A_{\mathrm{Pb}}}\times\frac{1}{3}\times 10^{-27}\ \mathrm{cm}^2\approx 2\times 10^{-30}\ \mathrm{cm}^2,$$

which is independent of the energy of the incident particle in the used energy range.

Effect of Altitude on the Frequency of Large Bursts

For further studies of the properties of the burst-producing radiation, it is important to determine the dependence of the burst frequency on the elevation above sea level. For this purpose one can use the data given in Table IV. The ratio of the burst rates at Huancayo and Cheltenham for corresponding threshold energies E is shown in the upper curve of Fig. 5. The lower curve of Fig. 5 represents the corresponding ratios between Teoloyucan and Cheltenham. In both curves we recognize the general character of this phenomenon, namely, that for smaller burst sizes, the ratio between two elevations is nearly constant and then increases rapidly with increasing burst magnitude. For Huancayo-Cheltenham the ratio has a value of 2.7 for threshold energies of 2×10^{10} ev and 5.6 for $E=2\times 10^{11}$ ev. The ratios at corresponding energies for Teoloyucan-Cheltenham are 1.4 and 2.3. These ratios have only an approximate value since they are obtained from data from different cosmic-ray meters. Different meters, even though located at the same place, record different burst rates, and hence a comparison of their absolute burst rates cannot give more than the right order of magnitude of the burst-rate ratio. That is, the locations of the two curves are not given with precision, but their shapes should be correct.

A second effect which has to be considered is the dependence of burst frequency upon geomagnetic latitude, as recently found by Jesse and Gill.[18] This effect runs as high as 30 ± 6 percent of the total burst rate at the equator. In order to get a more nearly correct value for the ratios of the burst frequencies, we compared the data from Huancayo and also from Teoloyucan with those obtained on board the *R.M.S. Aorangi* at corresponding geomagnetic latitudes. We used for the comparison with Huancayo a zone running from 15° N to 15° S and for Teoloyucan, 15° N to 35° N and 15° S to 35° S. The threshold energy corresponding to a burst of size 1 on the *Aorangi* is 3×10^{10} ev (Table III). Because of the comparatively small total number of bursts registered in the equatorial zone, we determined the value of the burst rate only for the one threshold energy, $E=3\times 10^{10}$ ev. The total number of bursts with corresponding energies greater than 3×10^{10} ev per cm^2 per minute is given for these zones as follows:

15 N–15 S	1.5×10^{-6}
15 N–35 N 15 S–35 S	1.8×10^{-6}
35 N–55 N 35 S–52 S	2.1×10^{-6}

The logarithm of the values between 15 N and 15 S is marked in the diagram of Fig. 2 as one big star. The value of the burst rate at the equatorial zone lies 30 percent below the corresponding value for Cheltenham. Thus a comparison of the Cheltenham and *R.M.S. Aorangi* meters indicates a latitude effect of about 30 percent, in agreement with the value of Jesse and Gill.

The ratios of the burst rates between Huancayo-*Aorangi* and Teoloyucan-*Aorangi* have the following values:

$$f_{3350}/f_0=3.6,$$
$$f_{2285}/f_0=2.0.$$

These results on the dependence upon altitude

[18] W. P. Jesse and P. S. Gill, Phys. Rev. **55**, 414 (1939).

of the frequency of large bursts are in qualitative agreement with the observations of Compton[19] and also of Bennett, Brown and Rahmel.[2] These investigators noticed that the ratio of the burst rate at high elevation to that at sea level increases for very large bursts. Korff[9] found a constant ratio (4.0) for burst rates of different burst sizes between Huancayo and Kensington. Inasmuch as the data used by Korff correspond to the first part of our curve up to energies 1×10^{11} ev (Fig. 5), the agreement seems satisfactory. Young and Street,[20] and also Montgomery and Montgomery[21] investigated the dependence of the burst rate on altitude up to an elevation of 4300 m and found much higher ratios. Their values lie between 10 and 26. These findings seem perfectly understandable considering the fact that these authors used smaller thicknesses of lead (around 4 cm) for the shielding of the ionization chamber.

The shapes of the curves (1) and (2) in Fig. 5 show that a more careful analysis of the energy distribution curves at different altitudes leads to the conclusion that the energy spectrum at sea level differs slightly from that at high elevations. Thus the distribution curve at sea level (Cheltenham) is distinctly steeper for energies greater than 10^{11} ev than at Huancayo and Teoloyucan. For the burst-producing radiation, we found that for energies $2\times10^{10}<E<10^{11}$ ev the absorption in air is given by the ratios $f_{3350}/f_0=3.6$ and $f_{2285}/f_0=2.0$. This means a considerable absorption of these rays in air, which is much larger than the corresponding mass absorption in dense materials at great depth. An absorption of a similar kind was considered by Kulenkampff[22] and also by Euler and Heisenberg[6] for mesotrons, where in addition to the energy loss by ionization the spontaneous decay of mesotrons has to be taken into account. For energies of the order of magnitude 10^{11} ev, the ionization loss in air is practically negligible. In order to account for the observed absorption, the actual length of path of the mesotrons in the atmosphere in which the disintegration takes place has to be over 100 km, in contrast to the observed 3.3 km. The observed absorption effect is therefore very much greater than one would expect for mesotrons alone. On the other hand, we obtain a complete explanation for the considerable absorption of the burst-producing radiation if we assume that at high altitudes there is present a very energetic component of soft radiation with energies over 10^{11} ev.

The presence of this radiation is confirmed by Auger[23] who investigated the dependence on altitude of very large atmospheric showers. The number of these showers increases very rapidly with elevation, even more rapidly than that part of the soft component which is responsible for the production of ordinary showers. The energy involved in Auger's showers runs from 10^{11} up to about 10^{15} ev and some of the secondary shower particles can penetrate even more than 10 cm of lead. It, therefore, seems reasonable to assume that very energetic photons (10^{11}–10^{13} ev) (and perhaps electrons) have a certain probability of forming a large burst in a lead thickness of 12 cm. The intensity of this soft radiation is very small at sea level. On the other hand, at higher elevations a much larger number of these rays should be present, which seems to be in perfect agreement with the observations. We, therefore, suggest that at sea level a certain part of the large bursts, corresponding to energies greater than 10^{11} ev, originate from photons (electrons).

The production of large bursts by photons (electrons) suggests a possible mechanism for the generation of mesotrons in the upper atmosphere.* Our analysis shows that this process has already taken place at elevations of 3300 m. However, the number of secondary mesotrons produced is extremely small at this altitude because of the low burst rate. On the other hand, at the top of the atmosphere where the number of energetic photons is more abundant, the creation of mesotrons becomes more probable and should contribute an appreciable part to the penetrating radiation. Some of the mesotrons can also be produced by an interaction of the following type between a photon and a

[19] A. H. Compton, Phys. Rev. **41**, 681 (1932).

[20] R. T. Young and J. C. Street, Phys. Rev. **52**, 552 (1937); **52**, 559 (1937).

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

[22] H. Kulenkampff, Verh. Dtsch. physik. Ges. (1938).

[23] P. Auger, Comptes rendus **207**, 907 (1938).

* In the symposium discussion by T. H. Johnson and W. Heisenberg, it appeared that mesotron production by protons must also be considered.

proton or neutron in the nucleus:

$$h\nu+P=N+Y^{+}$$
$$h\nu+N=P+Y^{-}$$

as suggested by Heitler[24] and confirmed[25] at altitudes of 25,000 feet.

[24] W. Heitler, Proc. Roy. Soc. **A166**, 529 (1938).
[25] M. Schein and V. C. Wilson, Phys. Rev. **54**, 304 (1938).

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