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Investigations on Large Cosmic-Ray Bursts*

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Observations on large cosmic-ray bursts have been performed at the altitude of 3500 meters with a model C meter surrounded by thick lead shields. G-M counters, connected to appropriate electronic circuits, were placed over these lead shields in order to record extensive air showers simultaneously with bursts. It is found that about 2 percent of the 100 particle bursts and about 14 percent of the 1000 particle bursts under 10.7 cm Pb are produced by extensive air showers. This fraction continues to increase with increasing burst size and becomes almost 100 percent for bursts of more than 4000 particles. The experimental observations are consistent with the assumption that the part of the burst-producing radiation which does not consist of air showers or of μ-mesons is attenuated in lead with the absorption mean-free-path of 346 ± 36 g/cm^2. The correction for the number of bursts produced by μ-mesons is based on a revision of the calculations of Christy and Kusaka; the revised calculation indicates that μ-mesons (spin 1/2) produce 68 ± 5 percent of the bursts in a model C meter under 10.7 cm Pb at sea level.

It is pointed out that the high energy N-component of the cosmic radiation (i.e., those particles having strong nuclear interactions with matter) can produce enough electronic radiation to account for the observed burst frequency, if $\int_0^1 z^2 p(z)dz=0.12$, where $p(\epsilon/E)d(\epsilon/E)$ is the probability per nuclear collision that an N-ray of high energy E produces electronic radiation of energy $(\epsilon, d\epsilon)$. The neutral meson mechanism satisfies this condition, provided one assumes that practically all of the energy of a high energy N-ray is carried away by mesons when a nuclear collision in lead takes place, and that one-third of this energy goes into neutral mesons. The calculations are made on the assumption that the absorption mean-free-path of high energy N-rays is 124 g/cm^2 in air, and that the directional intensity of the primary cosmic radiation with energies greater than E Bev is $0.12(4.5/E)^2$ sterad^{-1} cm^{-2} sec^{-1} at the top of the atmosphere.

I. INTRODUCTION

THIS paper is concerned mainly with ionization bursts which have been recorded with the model C meters,[1] and the burst size will be given in terms of a quantity called "number of particles." This quantity is defined as the number of ion pairs in the burst divided by the average number of ion pairs produced when a singly-charged particle at minimum ionization passes through the gas on the ion chamber in question. The number of particles in a burst equals on the average the number of particles in the shower which produced that burst, provided the shower is narrow compared with the dimensions of the ion chamber and contains only singly-charged particles at minimum ionization. In all other cases, the relation between the number of particles in a burst and the number of particles in the shower or "star" which might produce that burst is not unique.

In calculation of the number of particles in a burst, a knowledge of the average number of ion pairs produced by a traversal of one singly-charged particle, at minimum ionization, through the gas of the meter is needed. Schein and Gill[2] estimated the value of this quantity to be 96,000 ion pairs for the model C meter filled to a pressure of 50 atmos of pure argon.

This value can be verified indirectly as follows: Bennett *et al.*[3] found that the total amount of ionization produced by cosmic rays in a model C meter shielded with 10.7 cm Pb at sea level is 1.55×10^6 ion pairs/sec. When the figure of 96,000 ion pairs per particle is adopted, this means that 16.2 particles/sec pass through the meter under the above conditions. Now, almost all of the ionization produced by cosmic rays under 10.7 cm Pb at sea level is produced by the hard component of this radiation. Moreover, the cross section of the meter is 995 cm^2. Hence, the integrated intensity of the hard component at sea level is 1.63×10^{-2} cm^{-2} sec^{-1}. This value agrees with the value 1.68×10^{-2} cm^{-2} sec^{-1}, which was obtained by Greisen[4] using G-M counters.

We consider that it is still justifiable to assume that a single "particle" produces, on the average, 96,000 ion pairs in a model C meter filled to the pressure of 50 atmos of pure argon.

The fact that the collection time of the ions formed in a model C meter is of the order of 20 sec imposes a lower limit on the burst size which can be recorded reliably with this instrument. For example, the data of Bennett *et al.*[3] show that the average number of independent single particles which pass through the meter shielded with 10.7 cm Pb at 3240 meters elevation in 20 sec is approximately 900. Hence, in any given 20 seconds a fluctuation whose size is greater than 100 particles (3.3 times the standard deviation) takes place with the probability 9.6×10^{-4}. One-half of these fluctuations will cause deflections of the electrometer needle which are in the same direction as the deflections caused by bursts and consequently cannot be distinguished from the latter. Under these conditions a statistical fluctuation will be recorded as a burst, with size greater than 100 particles, at the average rate of once in every 11.6 hours. It will be seen later in the present paper [Sec. V(A)] that the observed frequency of bursts having more than 100 particles under 10.7 cm Pb at 3500 meters altitude is more than 6 per hour per model C

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* Assisted by a joint program of the ONR and AEC.

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[1] Compton, Wollan, and Bennett, Rev. Sci. Instr. **5**, 415 (1934).

[2] M. Schein and P. S. Gill, Revs. Modern Phys. **11**, 267 (1939), quoted as SG.

[3] Bennett, Brown, and Rahmel, Phys. Rev. **47**, 437 (1935).

[4] K. I. Greisen, Phys. Rev. **63**, 323 (1943).

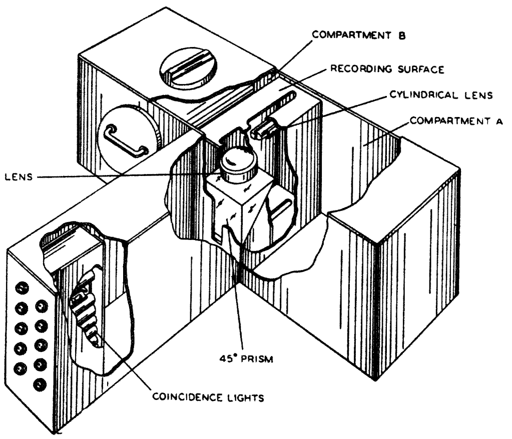

FIG. 1. Schematic perspective drawing of the camera arrangement which was used to record large bursts and air showers simultaneously.

meter. By repeating the calculation for bursts of more than 200 particles we can show that the number of statistical fluctuations, which can be mistaken for bursts of this size, is entirely negligible.

Since only bursts of 100 particles or more can be reliably recorded with a model C meter, such bursts have been arbitrarily called "large" cosmic-ray bursts.[5] Since the average amount of energy required to produce an ion pair in argon is 25.4 ev,[6] the energy of a large cosmic-ray burst exceeds 243 Mev.

In the year 1946, when this research was begun, at least one large burst problem presented itself clearly.[2,5,7] This was the problem of the production of large bursts at high altitudes. Because of the large atmospheric attenuation in the frequency of these bursts, it was evident that ordinary mesons (μ-mesons) could not produce all of them; ordinary mesons with energies of 1.5×10^{10} ev or more (that is, with the amount of energy required to produce a large burst according to the mechanism described by CK) suffer very little absorption in going from mountain altitudes to sea level. Therefore, the frequency of bursts produced by such mesons must also undergo a negligible change between these altitudes. This indicates that the majority of large bursts observed at high altitudes must arise from another origin besides the one described by CK for sea-level bursts.

II. APPARATUS

(A) Type of Apparatus

It was realized that the increase in burst frequency observed on going from sea level to mountain tops might be due to the more frequent presence of very energetic air showers at the higher altitudes. Consequently, it was decided to use an experimental arrangement similar in principle to that which was used by Lapp,[5] and to perform experiments at Climax, Colorado (altitude 3500 meters, mean atmospheric pressure 675 g/cm^2). This type of experimental set-up has two important fundamental difficulties associated with it:

(1) The fact that the air showers and the bursts in question are recorded separately on a slowly moving strip of photographic paper makes it impossible to resolve the records of these events when they occur within approximately ten seconds of one another. This causes an apparent or accidental coincidence rate.

(2) It is possible for an air shower to occur in true coincidence with a burst and at the same time not be the cause of that burst. An event of this kind could happen, for example, if a single penetrating particle first produced an air shower, and later produced a burst with the remainder of its energy; the air shower could conceivably actuate the shower detecting arrangement and at the same time be altogether incapable of penetrating the shield which surrounds the ionization chamber.

Measurements and arguments which estimate the magnitudes of these effects will be given later [Secs. IV(B) and VI(B)].

(B) The Recording Camera

A schematic perspective drawing of the camera arrangement is shown in Fig. 1. The position of the electrometer needle is recorded by means of a cylindrical lens in exactly the same way as it was done in the formerly used camera of the model C meter.[1] In addition, the camera is equipped with "coincidence" lights, each of which can be flashed by means of an outside circuit. Each coincidence light is enclosed in a separate cylindrical compartment, and all of the compartments are in line and placed flush against a single long slit. This ensures that only a short unique portion of this slit is illuminated by any given coincidence light. An image of the slit is focused in the smaller slot of the "recording

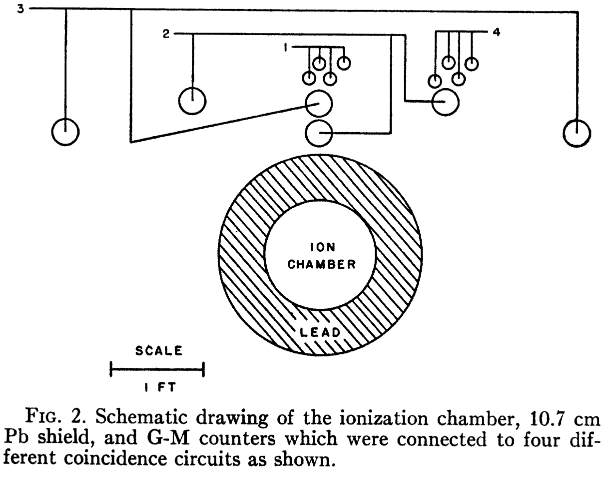

FIG. 2. Schematic drawing of the ionization chamber, 10.7 cm Pb shield, and G-M counters which were connected to four different coincidence circuits as shown.

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[5] R. E. Lapp, Phys. Rev. **69**, 321 (1946).

[6] Rutherford, Chadwick, and Ellis, *Radiations from Radioactive Substances* (Cambridge University Press, London, 1930).

[7] R. F. Christy and S. Kusaka, Phys. Rev. **59**, 414 (1941), quoted as CK.

surface" by means of the 45° prism and the lens shown. The position of the slit is so chosen that its image on the recording surface is exactly in line with the image of the electrometer lamp [Sec. II(D)]. A 5-inch-wide photographic paper (Eastman Kodak 797 Emulsion), pressed against the recording surface, is transferred at a continuous rate of about six inches per hour from compartment A to compartment B by means of a driving mechanism which is not shown in Fig. 1.

(C) Over-All Arrangement of Apparatus

A schematic drawing of the ionization chamber surrounded by 10.7 cm Pb, together with the four coincidence sets of G-M counters which were used to record extensive air showers, is shown in Fig. 2. The counters were approximately one foot in length, and their diameters were one inch and two inches. The electronic circuits were of the conventional types. The argon used to fill the ionization chamber was 99.8 percent pure.

(D) The Photographic Record

A replica of part of a record, obtained from the camera when 10.7 cm Pb surrounded the meter, is shown in Fig. 3. The sensitivity of the electrometer was adjusted so that the distance between two consecutive rulings corresponds to a burst of 100 particles. The rows 1, 2, 3, and 4 of marks were produced when the respective G-M counter sets 1, 2, 3, and 4 (Fig. 2) were actuated by air showers.

Figure 3 also reveals the effects of the following cycle of operations:

(1) Once every hour the electrometer lamp is brightened, a potential of $\frac{1}{2}$ volt is put on the electrometer needle, and the coincidence lamps are lit of approximately 20 seconds.

(2) The electrometer lamp is dimmed and the electrometer needle is grounded during the 5 seconds immediately following operation 1.

(3) Once every 15 minutes, every fourth interval being omitted in favor of operations 1 and 2, the electrometer lamp is dimmed and the electrometer needle grounded for approximately 25 seconds.

III. EXPERIMENTS

The first experiments were performed with 10.7 cm Pb around the meter; in later experiments the experimental arrangement was altered to accommodate thicker shields. In order to use these shields, it was necessary to move the box which contained the electrometer further away from the rest of the meter. This alteration provided room for an increase in the shield thickness around the top hemisphere of the meter.

The experiments were then continued with a total shield of 26.7 cm Pb around the top hemisphere and 10.7 cm Pb around the bottom.

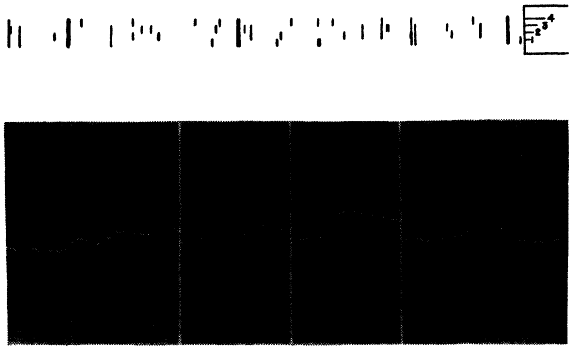

FIG. 3. Replica of part of a record obtained from the camera used in conjunction with the model C meter surrounded by 10.7 cm Pb at the elevation of 3500 meters.

Finally, the shield was increased further by placing a rectangular slab of solid lead symmetrically on top of the 26.7-cm absorber.[8] The dimensions of this slab were 50″×48″×12″, and the perpendicular distance from the center of the ion chamber to the bottom face of the slab was approximately 24″.

IV. ELIMINATION OF ERRORS

(A) Errors in the Determination of Burst Frequencies

In this work a comparison is made between the burst rates under different thicknesses of shielding. Approximately three months is required to obtain statistically reliable data for any one shield thickness. Therefore, corrections must be made for the changes in the sensitivity of the meter which took place during these long periods of time.

The following changes took place:

(1) A change in the construction of the meter was performed (Sec. III). This alteration caused roughly a 45 percent increase in the electrical capacity of the ion-collecting system. To eliminate any error which might arise from this change, the new capacity was accurately measured and the observations with the 10.7-cm Pb shield were partly repeated, thereby providing a few points through which the size-frequency curve (plotted on double log paper) should pass. The older data were used to determine the slope of this curve. This procedure is feasible because the curves in question are straight lines. Furthermore, an accurate knowledge of the old capacity is not required. In Fig. 4 the points obtained from the older data are shown in relation to the curve which "passes through them."

(2) During the observations a gas leak developed in the meter. A daily record of the pressure was kept during the complete period of the observations. According to Compton *et al.*,[1] for small pressure variations in the neighborhood of 50 atmos, the ionization coefficient of argon is approximately proportional to $(p+13.2)$, where p is the absolute pressure at 0°C

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[8] I am indebted to Professor B. Rossi of M.I.T. and to the Arkansas Valley Smelting Company, Leadville, Colorado, for lending the lead bricks used in this slab.

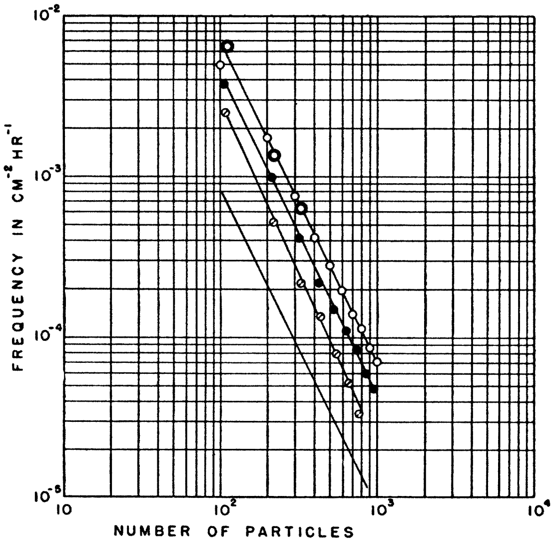

FIG. 4. Integral size-frequency curves for large cosmic-ray bursts under several thick lead shields [Sec. V(A)] at the altitude of 3500 meters. The curve, on which no points are marked, represents the Cheltenham (sea level) data which was published by Lapp (reference 5).

measured in atmospheres. The *average* pressure during the period in which the observations for a given shield thickness were recorded was taken as the pressure corresponding to that shield thickness. The magnitude of the correction can be seen in Fig. 4. All of the experimental points plotted in this figure would lie exactly on the ordinates, corresponding to 100, 200, 300, etc., particles, if the correction were not applied. The application of the correction moved the points slightly towards the right.

(B) Errors in the Relation of Bursts to Air Showers

The observed coincidence rate between air showers and bursts must be corrected for accidental coincidences [Sec. II(A)]. The accidental coincidence rate was estimated as follows: A large number of artificial marks were arbitrarily put by hand on the electrometer trace of one of the records, and these artificial marks were analyzed in exactly the same way as the burst marks were analyzed. The probability that an artificial mark will coincide with the record of an air shower must be equal to the probability that a burst mark will coincide *accidentally* with the record of an air shower. If P_t, P_m, and P_a are the respective percentages of bursts which actually coincide, apparently coincide, and accidently coincide with air showers, then

$$P_t = (P_m - P_a)/(1 - P_a/100).$$

TABLE I. Number of hours data and probable errors associated with the burst frequencies observed under the various thick lead shields at 3500-meter elevation.

Experiment (a′) 1746 hours		Experiment (a″) 520 hours		Experiment (b) 1424 hours		Experiment (c) 664 hours	
Number of particles	Probable error (%)	Number of particles	Probable error (%)	Number of particles	Probable error (%)	Number of particles	Probable error (%)
100	0.9	111	1.2	106	0.9	109	1.7
200	1.5	221	2.5	212	1.8	218	3.6
300	2.2	332	3.7	318	2.8	327	5.6
400	2.9	...	...	424	3.9	436	7.2
500	3.6	...	...	530	4.7	545	9.4
600	4.3	...	...	636	5.4	654	11.6
700	5.1	...	...	742	6.3	763	14.4
800	5.7	...	...	848	7.4	...	...
900	6.5	...	...	954	8.3	...	...
1000	7.2	...	...	...	...	...	...

V. EXPERIMENTAL RESULTS

(A) Burst Frequencies

The integral size-frequency curves are shown in Fig. 4. The centers of the open circles mark the points obtained with 10.7 cm Pb around the meter; the more prominent open circles represent the points which were obtained after the meter had been altered (Sec. III), and the less prominent ones represent the points which are obtained prior to this alteration and which were located as described above [Sec. IV(A)]. Similarly, the closed circles represent the frequencies observed with 26.7 cm Pb around the top hemisphere and 10.7 cm Pb around the bottom hemisphere, while the circles with diameters have their centers located at the points obtained when the flat slab of lead (Sec. III) was added to the 26.7-cm hemispherical lead absorber. Hereafter, these three lead shields, together with the respective experiments performed with them, will be referred to by the symbols (a), (b), and (c), respectively. The part of experiment (a) performed before the meter was altered and the part performed after the alteration will be called (a′) and (a″), respectively, in cases where a distinction should be made between them. The sea level data which was published by Lapp[5] are also shown in Fig. 4.

The probable errors associated with the various points on Fig. 4, in addition to the number of hours data obtained with each shield, are given in Table I.

(B) Relation of Bursts to Air Showers

The rates at which bursts, greater than the given sizes under shield (a), coincided with the various types (Fig. 2) of air showers are recorded in Table II, where they are expressed as a percentage of the corresponding total burst rates. These rates are corrected for accidentals [Sec. IV(B)]. The accidental rates are also given in Table II.

In a few instances, the negative numbers in Table II arose when the accidental rate happened to exceed the observed rate. These negative numbers of course have no physical significance, but their magnitudes give us an idea of the magnitudes of the errors involved.

It was evident from the results given in Table II that the number of bursts produced by air showers is relatively small, and furthermore that the greater majority of the air showers which coincided with bursts

TABLE II. Number of bursts, having the given minimum sizes under shield (a), which coincide with air showers. The number is expressed as a percentage of the corresponding total number of bursts. The obvious meaning should be attached to the notation used to describe the type of shower coincidence—for example, (124) means that *only* the G-M counter sets 1, 2, and 4 were tripped, and so on.

Number of particles	Percentage of bursts in coincidence with air showers Type of shower coincidence														
	(1234)	(123)	(124)	(134)	(12)	(13)	(14)	(1)	(234)	(23)	(24)	(2)	(34)	(3)	(4)
100	1.9	0.1	0.1	0.3	0.1	0.1	0.1	0.8	0.3	0	−0.3	−0.9	0.5	0.3	−1.0
200	3.3	0	0.1	0.5	0.2	0.1	0.1	1.2	0.1	0.2	−0.4	−1.3	0.4	0.3	−0.7
300	5.9	−0.1	0.4	0.5	−0.3	0	0.1	1.2	0.6	0.5	−0.5	−0.1	0.4	0.1	−2.0
400	7.1	0.2	0.6	0.6	−0.1	−0.5	0.1	1.5	1.2	0.1	−0.4	0.4	0.3	0.6	−1.6
500	8.3	0.6	1.0	0.6	0.2	−0.5	0.2	1.0	1.5	0.1	−0.7	2.3	0.4	0.7	−2.5
600	8.4	0.5	0.9	0.9	0.5	−0.5	−0.2	1.4	1.2	0.4	−0.7	3.7	0.5	0.2	−2.8
700	10.0	0.2	1.4	1.4	0.2	−0.5	−0.2	1.9	2.0	0.1	−0.7	5.5	0	1.2	−3.7
800	11.4	0.5	1.8	1.8	0.5	−0.5	−0.2	0.7	0.6	0.4	−0.7	6.8	0	2.1	−3.5
900	13.7	0.9	1.2	2.6	−0.6	−0.5	−0.2	0.1	1.0	0.8	−0.7	−2.2	0	2.4	−4.5
1000	13.7	1.2	1.5	3.3	−0.6	−0.5	−0.2	0.4	1.3	1.1	−0.7	−1.9	0	1.5	−4.5
Accidental rates	2.1	0.6	0.2	0.2	0.6	0.5	0.2	1.3	0.4	0.7	0.7	3.5	0	2.0	4.3

had a high probability of tripping *all* of the shower-counting circuits [Sec. VI(B)]. Consequently, in the subsequent analysis of the data only the air showers which actuated all of the circuits were counted. The results are shown in Table III, where the percentages of bursts which are coincident with air showers and the actual frequencies of extensive air showers which occur simultaneously with bursts of the given minimum sizes are given.

A few very large bursts were observed. These were capable of deflecting the electrometer needle off-scale, and, consequently, each one contained more than 4000 particles. Such events exhibit a strong tendency to coincide with air showers; 7 out of the 9 "off-scale" bursts observed during experiments (a′) and (a″) coincided with air showers, and the same is true of 3 out of the 4 observed during experiment (b). No "off-scale" bursts was recorded during experiment (c).

VI. DISCUSSION OF EXPERIMENTAL RESULTS

(A) Absorption Rates

From Fig. 4, the burst frequencies under shield (a) are attenuated by the factor 8.5 between Climax and sea level. Furthermore, the fact that the sea-level curve is parallel to the corresponding high altitude curve indicates that this attenuation is independent of the burst size within the range of burst sizes given. This absorption factor is roughly twice the corresponding factors which have been reported by SG and by Lapp for the absorption between Huankayo, at 3350 meters altitude, and sea level.[9] It might appear that this discrepancy points to an error either in the author's data or in the Huankayo and Cheltenham data reported by SG and Lapp. However, from Forbush's result it is not impossible that this might be a genuine effect. Furthermore, the fact that the burst rate recorded in the Cheltenham meter has not changed during the past ten years indicates that if there is any appreciable error at all such an error is probably in the Huankayo data which has been changing with time. No use is made of the Huankayo data in this paper.

From Fig. 4 the burst frequency under shield (a) is 1.6±0.06 times the corresponding frequency under shield (b), and this factor is again independent of burst size. The error in this figure is due to the errors in locating the size-frequency curves.

If one assumes that 68±5 percent [Sec. VII(B)] of the bursts under shield (a) at sea level are produced by μ-mesons which are not absorbed appreciably in any of the thicknesses of lead or air in question, then the above figures indicate that the part of the burst-producing radiation which is not composed of μ-mesons must be absorbed by the factor 25±4 on going from Climax, at the atmospheric depth 675 g/cm^2, to sea level. In like manner, this radiation is absorbed by the factor 1.7±0.09 on traversing the 181 g/cm^2 difference in lead thickness between shield (a) and shield (b). These latter figures correspond respectively to absorption mean free paths of 124±8 g/cm^2 in air, and 346±36 g/cm^2 in lead. In calculating these absorption lengths, we assume that a simple exponential absorption

TABLE III. Rate of coincidences between large air showers and bursts of the given minimum sizes under various lead shields at 3500 meters elevation. Percentage column gives this rate as a percentage of the total burst rate, and column *F* gives the actual rate per 1000 hours, at which such events are observed in the model C meter.

Number of particles	Shield (a)		Shield (b)		Shield (c)	
	%	*F*	%	*F*	%	*F*
200	3.3	37.0	0.4	4.0	0.2	1.3
300	5.9	30.0	1.0	4.1	5.6	12.3
400	7.1	20.5	0.2	0.4	6.3	8.4
500	8.3	15.8	2.1	2.9	12.3	9.7
600	8.4	11.4	4.6	4.9	13.7	7.1
700	10.0	9.2	7.2	5.8	16.3	5.4
800	11.4	8.2	7.2	4.1	16.7	3.3
900	13.7	7.2	8.7	4.0	15.8	2.2
1000	13.7	5.8	11.1	4.5	7.8	0.9

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[9] I am indebted to Dr. Scott E. Forbush of the Carnegie Institution, Washington, D. C., for telling me about a similar effect, namely, that the burst frequency at Huankayo has approximately doubled itself during the past ten years, while the frequency at Cheltenham (sea level) has remained constant.

takes place in lead, and that the law discussed in the Appendix of this paper describes the absorption in the atmosphere.

The curve (Fig. 4) obtained with shield (c) is not parallel to the other curves. This means that the absorption is no longer independent of the burst size. We choose in this case to discuss only the bursts which have the minimum size of 300 particles; as the bursts become smaller, the analysis of them becomes more difficult and less reliable; statistical errors are more significant for the larger bursts. The radiation which produces these bursts is absorbed by the factor 1.75 when the shielding is altered from the arrangement (b) to the arrangement (c). On the other hand, if one assumes that the burst-producing radiation is composed, in the manner already described, of μ-mesons and of an "absorbable" radiation having a mean free path of 346 g/cm^2 in lead and that all of this latter radiation strikes the lead slab of shield (c), one can show that an absorption of 2.23, should be introduced by the change from shield (b) to shield (c). The fact that these two absorption factors do not agree indicates either that the absorbable portion of the burst-producing radiation becomes "harder" as it passes through matter, or that some part of this absorbable radiation fails to encounter the flat slab of shield (c), or both.

(B) Relation of Bursts to Air Showers

From Table II it can be seen that the air showers which coincide with bursts have a high probability of tripping *all* of the shower recording circuits. This fact can be used to decide between the two possibilities [Sec. II(A)]; (1) that the air showers themselves actually penetrate the lead shields and produce the bursts, and (2) that each of these air showers is produced by a single penetrating particle which proceeds to the inside of the lead shield with the remainder of its energy to produce there another shower which causes the coincident burst. If (1) were true, then the extensive air showers in question should have a high particle density and should, as a result, exhibit a high probability of tripping *all* of the shower recording circuits. This prediction agrees with the results in Table II. The possibility (2), however, by its very nature, does not require that the air showers should have a high particle density. Therefore, such air showers would more frequently appear with low particle densities; and, consequently, the majority of them would have low probabilities of tripping one of the shower recording circuits. This latter fact would make the probability of tripping *all* of the circuits much less than the probability of tripping just a *few*, a prediction which is contrary to the experimental results in Table II. We are therefore led to the conclusion that (1) is the correct possibility.

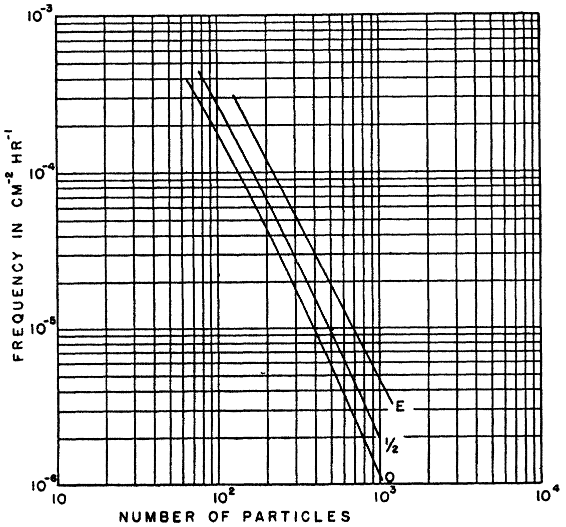

FIG. 5. Integral size-frequency curves for large bursts under 35 cm Fe at sea level. Curve "*E*" represents the experimental results of Lapp. The other two curves give the theoretical estimates of the rates at which μ-mesons should produce these bursts, curve "$\frac{1}{2}$" corresponding to spin $\frac{1}{2}$, and curve "0" corresponding to spin 0 for the μ-meson. The theoretical estimates are based on a revision (see text) of the calculations of Christy and Kusaka.

Table III gives the rates at which bursts under the various lead shields are produced by extensive air showers. Only those air showers which actuated all of the shower recording circuits are counted in this table. The statistical accuracy of the numbers shown leaves very much to be desired—approximately 1000 hours of data were obtained with each shield; therefore, the numbers shown in columns *F* represent the orders of magnitude of the actual total number of events observed in each case. The poor statistical accuracy of these figures is also evident from the fact that the numbers in columns *F* for shield (b) and (c) are not monotonic—the numbers of an *integral spectrum* should always be monotonic.

Despite these shortcomings, the over-all magnitudes of the numbers in the various columns *F* show that a strong attenuation in the number of bursts produced by air showers is introduced when shield (a) is replaced by shield (b). The corresponding attenuation which accompanies the further change from shield (b) to shield (c) is evidently much smaller. These facts, when taken at their face values, indicate that many of the air showers which produce large bursts under shield (a) are electron showers, whereas the air showers which produce these bursts under thicker shields tend to assume a penetrating nature.

The percentage of bursts which are produced by air showers evidently increases with increasing burst size. This rate of increase continues as we go into the still larger bursts, as is evident from the fact that the greater majority of the "off-scale" bursts [Sec. V(B)] are produced by air showers. For absorbers (b) and (c), most of the coincident showers coincide with the very largest bursts and very few with the smaller bursts. This fact tends to be obscured by the use of an integral spectrum.

VII. REVISIONS IN THE CALCULATIONS OF CHRISTY AND KUSAKA

(A) Model C Meter under Iron

The calculations of CK are influenced strongly by the values which are adopted for the mass of the meson, the intensity of mesons at sea level, and the equivalent critical shower energy of the material surrounding the meter. Since the time CK's paper was published, better estimates of the mass of the μ-meson and of the intensity of sea level mesons have become available. In addition, Lapp has performed burst observations at sea level using a thick shield of pure iron around the meter.

We shall therefore revise the calculations of CK assuming that the mass of the μ-meson[10–12] is 216 m_e, and that the vertical intensity of sea-level mesons[13] is 8.8×10^{-3} cm^{-2} sec^{-1} sterad^{-1}. The main uncertainty in the critical energy is removed when the calculations are made for a shield of the same element throughout. The critical energy for iron is 25.9 Mev.[14]

The results of this calculation are shown in Fig. 5; curves "0" and "$\frac{1}{2}$" are the calculated curves for μ-mesons of spin 0 and $\frac{1}{2}$, respectively. The curve "E" is the straight line which was drawn by Lapp[5] through the points which were obtained from his experimental observations under 35 cm Fe at sea level.

The results of recent experiments[12,15] on the radioactive decay of the μ-meson are consistent with this meson having spin $\frac{1}{2}$. Furthermore, there is no evidence indicating that the interaction of high energy μ-mesons with matter is any higher than the *minimum* amount which was calculated by CK. It seems, therefore, justifiable to regard curve "$\frac{1}{2}$" as representing not only the minimum number, but also the actual number of bursts which are produced under 35 cm Fe at low altitudes by μ-mesons. Thus, from Fig. 5, roughly 54.5 percent of the 300 particle bursts under 35 cm Fe at sea level are produced by μ-mesons.

(B) Model C Meter under Lead

An estimate of the number of bursts produced by μ-mesons in a model C meter surrounded by a large thickness of lead can be furnished if the following assumptions are made:

(1) The portion of the burst-producing radiation, which does not consist of μ-mesons, is made up from a radiation whose cross sections for production of bursts and for absorption are proportional to $A^{\frac{2}{3}}$, where A is the atomic weight of the material through which this radiation might pass.

(2) The absorption mean free path of this radiation[16] in lead is 346 g/cm^2.

It then follows that the ratio of the number of bursts not produced by μ-mesons to the number produced by μ-mesons must vary with shield element approximately like $A^{\frac{2}{3}}/Z^2$, provided the thickness of the shield divided by the absorption mean free path of the absorbable burst-producing radiation is kept constant. Furthermore, the value of this ratio is not appreciably affected by the presence of the 1.25-cm Fe shell of the meter, because of the following:

The thickness of this shell is less than one radiation unit; consequently very little shower multiplication can take place in such a thickness. Therefore, very few burst-producing showers will be initiated in the iron shell, and its essential effect is merely to reduce the number of particles in the showers which have already been well developed in the lead. The extent of this attenuation in the iron shell must, for a given size of shower, be approximately independent of how the shower was initiated in the lead. Thus, even though the presence of the iron shell does effect the actual burst frequencies, it does not appreciably effect the ratios between the rates at which bursts are produced by the different processes.[17]

Since μ-mesons produce roughly 54.5 percent of the large bursts under 35 cm Fe at sea level [Sec. VII(A)], the ratio of the number of bursts not produced by μ-mesons to the number produced by μ-mesons equals 45.5/54.5. Hence, this ratio becomes

$$(45.5/54.5)(207.2/55.8)^{\frac{2}{3}}(26/82)^2 = 0.203$$

when the meter is surrounded by 410 g/cm^2 of lead at sea level.[18]

A reduction in the thickness of the lead shield from 410 g/cm^2 to 121 g/cm^2, that is, to the thickness of the lead part of shield (a), will increase this ratio by the factor exp(389/346) to the value 0.47. This latter figure signifies that roughly 68 percent of the large bursts in a model C meter, surrounded by 10.7 cm of lead at sea level are produced by μ-mesons (spin $\frac{1}{2}$). CK would have obtained this result if, in addition to using the above values for the mass of the μ-meson and for the intensity of μ-mesons at sea level, they had also taken the value of 15.8 Mev for the equivalent critical shower energy of 1.25 cm Fe surrounded by a large thickness of lead.

The principal sources of error in the above calculation are in the mass of the μ-meson in the treatment of cascades, and in the use of Lapp's data. The error in the mass of the μ-meson is 2 percent, and its effect is 4 percent. From the statements of CK we limit the error

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[10] A. S. Bishop, Phys. Rev. **75**, 1468A (1949).

[11] J. G. Retallak and R. B. Brode, Phys. Rev. **75**, 1716 (1949).

[12] Leighton, Anderson, and Seriff, Phys. Rev. **75**, 1432 (1949).

[13] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

[14] L. Jánossy, *Cosmic Rays* (Clarendon Press, Oxford, 1948).

[15] J. Steinberger, Phys. Rev. **74**, 500 (1948).

[16] At first sight, it might appear as if we are begging the whole question here: first, the number of bursts produced by μ-mesons was used to arrive at the figure 346 g/cm^2 [Sec. VI(A)] and now the figure 346 g/cm^2 is being used to find the number of bursts produced by μ-mesons. A closer examination will show, however, that a method of successive approximations is in fact being employed.

[17] We are referring to the cases in which electrons cause the greater part of the ionization in the burst.

[18] According to the assumptions stated above, 410 g/cm^2 of lead plus 1.25 cm of iron contain the same number of absorption mean free paths as does 35 cm Fe.

in the treatment of cascades to 5 percent. Significant errors (if any) in Lapp's data are systematic errors; and since we have no reason for thinking that there are such errors [Sec. VI(A)], we shall assume that they are not significant.

In view of these possible errors, we conclude that 68±5 percent of the large bursts in a model C meter surrounded by 10.7 cm of lead at sea level are produced by μ-mesons.

VIII. RELATION OF BURSTS TO THE ELECTRONIC RADIATION PRODUCED IN NUCLEAR COLLISIONS

(A) General Calculation

At this point, we shall perform a general calculation by letting $p(\epsilon/E)d(\epsilon/E)$ be the probability per nuclear collision[19] that a high energy N-ray, with energy E, will transfer the energy $(\epsilon, d\epsilon)$ to a small number of electronic rays, electrons or photons. Then a condition which must be satisfied by $p(\epsilon/E)$ can be found by comparing the results of this calculation with the experimental results. Later [Sec. VIII(B)], an expression for $p(\epsilon/E)$ will be developed from a mechanism proposed for the production of electronic radiation by N-rays, and the condition developed in this section will be applied to this expression.

The following facts and assumptions will be used in the calculation:

(1) The absorption mean free path of high energy N-rays is 124 g/cm^2 in air, and 346 g/cm^2 in lead. The collision mean free path in lead is 140 g/cm^2, this latter figure corresponds to the geometrical cross section $\pi(1.5\times10^{-13})^2A^{\frac{2}{3}}$.

(2) The primary cosmic-ray protons have (i) a directional intensity[13] of 0.12 sterad^{-1} cm^{-2} sec^{-1}, (ii) a cut-off energy[14] of 4.5 Bev, and (iii) an inverse square integral spectrum[20] for energies greater than 4.5 Bev.

(3) The manner in which a shower develops from a small number of electronic rays is correctly described, for our purposes, by the corresponding algebraic formulas of CK. The equivalent critical shower energy for the model C meter surrounded by a large thickness of lead is 15.8 Mev [Sec. VII(B)].

It follows that the integrated intensity of the primary cosmic-ray protons having the minimum energy of E Bev is $2\pi(0.12)(4.5/E)^2$ cm^{-2} sec^{-1}, when E is greater than 4.5 Bev. Hence, the corresponding integrated intensity of high energy N-rays at Climax (depth parameter 675/124=5.44) becomes $2\pi J(-5.44)\times0.12\times(4.5/E)^2$, which equals $9.2\times10^{-3}/E^2$ cm^{-2} sec^{-1} (see Appendix).

On the basis of the above, one finds that the N-component at Climax should produce bursts of more than S particles in the model C meter, surrounded by 10.7 cm Pb, at the rate

$$(530/S^2)\int_0^1 z^2p(z)dz \text{ cm}^{-2}\text{ hr}^{-1}.$$

An examination of Fig. 4 shows that the integral frequency of bursts which are not produced by μ-mesons is $64.2/S^2$ cm^{-2} hr^{-1}. Hence, if these bursts are produced by the N-component, we have

$$\int_0^1 z^2p(z)dz=0.12.$$

(B) The Neutral Meson Hypothesis

The possibility that neutral mesons, which decay in less than 10^{-13} sec into two gamma-rays, might be responsible for much of the electronic part of the cosmic radiation has been suggested.[21–24] Strong experimental evidence in favor of the existence of such a meson has emerged from further cosmic-ray investigations as well as from the study of gamma-rays which are produced by artificially accelerated high energy protons.[25–27]. Pairs of gamma-rays from targets bombarded with high energy x-rays have also been observed.[28] The results of all of these experiments conform to the "neutral meson hypothesis." The results of Steinberger *et al.*[28] indicate further that neutral mesons and positive π-mesons are produced at roughly equal rates.

Since a neutral meson, account of its short life, is transformed almost immediately into electronic radiation, we may say that the probability for the production of a shower equals the probability for the production of neutral mesons having the same total energy. In addition, we shall assume that a high energy N-ray loses all of its energy when it makes a nuclear collision in lead, and that one-third of this energy goes into neutral mesons.

Hence for this mechanism

$$p(\epsilon/E)d(\epsilon/E)=\delta(\epsilon/E-1/3)d(\epsilon/E).$$

This probability function gives

$$\int_0^1 z^2p(z)dz=\int_0^1 z^2\delta(z-\tfrac{1}{3})dz=0.11,$$

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[19] Arguments which justify the adoption of this kind of probability function are given by W. Heitler and L. Jánossy, Proc. Phys. Soc. (London) **A62**, 374 (1949).

[20] We assume an inverse square spectrum because it gives approximately the correct size-frequency relation for large bursts and because experimental evidence to the contrary does not exist for the energies considered here. The burst-producing rays considered have energies of more than 30 Bev; and since these are secondary rays, they must have come from primaries whose energies are very much larger than this.

[21] J. R. Oppenheimer, Phys. Rev. **71**, 462A (1947).

[22] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).

[23] K. I. Greisen, Phys. Rev. **73**, 521 (1948).

[24] B. Rossi, Revs. Modern Phys. **21**, 104 (1949).

[25] Kaplon, Peters, and Bradt, Phys. Rev. **76**, 1735 (1949).

[26] Bjorklund, Crandall, Moyer, and York, Phys. Rev. **77**, 213 (1950).

[27] Gregory, Rossi, and Tinlot, Phys. Rev. **77**, 299 (1950).

[28] Steinberger, Panofsky, and Steller, Phys. Rev. **78**, 802 (1950).

which satisfies the experimental requirement expressed in Sec. VIII(A). This result seems to indicate that the neutral meson hypothesis is fruitful in accounting for the observed frequency of large cosmic-ray bursts at high altitudes.

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APPENDIX

The Carnegie model C meter, in so far as it possesses spherical symmetry, has a sensitivity to ionizing particles which is independent of the zenith direction from which these particles approach. Therefore, this instrument will always record the integrated intensity of the events which it detects.

In the work reported here, it is therefore the integrated intensity of the burst-producing radiation which is represented. We wish to express our results under the assumptions that the directional intensity of this radiation is absorbed exponentially in matter and that it is hemispherically isotropic at the top of the atmosphere. The atmosphere itself is pictured as a flat slab having a finite thickness and infinite horizontal dimensions.

Let us use the absorption mean free path of the directional radiation as our unit of distance, and for convenience call the depth of the point of observation measured in this unit the *depth parameter* of the point. It is also convenient to use the directional intensity and the integrated intensity of the radiation at the top of the atmosphere as units of directional intensity and integrated intensity, respectively.

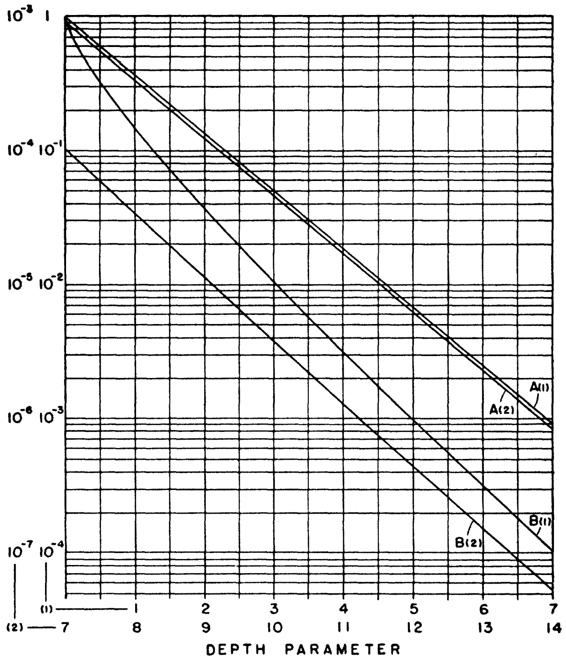

FIG. 6. Variation with depth parameter of (A) the vertical intensity, and (B) the integrated intensity of a radiation whose directional intensity is absorbed exponentially in matter and which is isotropic at zero depth. The depth parameter is the depth measured in absorption mean free paths.

When this convention is adopted, the integrated intensity, which we shall call $J(-y)$, at the point whose depth parameter is y, becomes

$$J(-y)=\int_0^{\pi/2}\exp(-y\sec\theta)\,\sin\theta d\theta=\exp(-y)+yEi(-y),$$

where

$$Ei(-y)\equiv-\int_y^{\infty}t^{-1}\exp(-t)dt.$$

A graph of $J(-y)$ *versus* y is shown in Fig. 6, curve B.

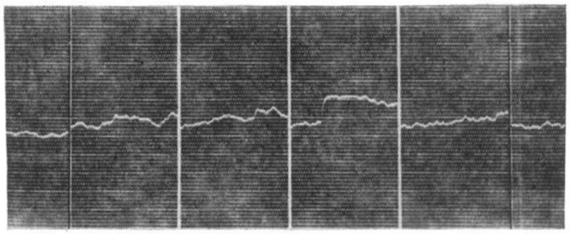

FIG. 3. Replica of part of a record obtained from the camera used in conjunction with the model C meter surrounded by 10.7 cm Pb at the elevation of 3500 meters.