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Cosmic-Ray Ionization Bursts in an Unshielded 8-Inch Pressurized Sphere at Sea Level*

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Two thin-walled ($\frac{1}{16}$-inch steel = 1.22 g cm^{-2}) spherical ion-chambers, 8 inches in diameter, filled with best quality (99.8%) commercial cylinder argon at 50 atmospheres, have been used to measure cosmic-ray ionization bursts near sea level. The bursts in one ion-chamber were measured by means of a vibrating reed electrometer and in the other by an electrometer tube and dc feedback amplifier. The results from the two ion-chambers agreed to within two percent except that the smallest bursts could not be detected with the vibrating reed instrument. The integral size-frequency distribution of the bursts is given for sizes from 2×10^4 to 3×10^7 ion-pairs and the corresponding frequencies range from 3×10^4 to 3×10^{-4} bursts per hour. The size-frequency distribution has been separated into five components identified respectively with single μ mesons, electrons, single protons, star processes, and extensive electron showers. These components have been resolved by comparison of the unshielded distribution with that obtained under a 27-cm lead shield and the interpretation of their origin has been confirmed by coincidence experiments involving Geiger counters, a Čerenkov proton selector, and other ion-chambers. The existence of a sharp kink in the size-frequency distribution curve, similar to that reported by Carmichael and Chou in 1939, is confirmed.

1. GENERAL

MUCH of the published experiment data[1–27] on the size and frequency of cosmic ray ionization bursts is of limited value because the apparatus used was not capable of measuring the bursts over a large range of size; most of these size-frequency distribution curves extend over less than one decade of burst size. A range of size of about two decades was achieved by one[28] of the authors in 1936 using a quartz fiber electroscope. We have recently developed ion-chambers and measuring equipment which are capable of dealing in one experimental run with bursts differing in size by more than three decades.

A primary reason for embarking upon this work was to repeat, and if possible confirm, with completely new and different apparatus, the measurements previously made by Carmichael in 1936[28] and by Carmichael and Chou in 1939.[29] These earlier measurements were discussed in detail in 1948[30] with particular reference to the apparently composite nature of the size-frequency distribution curve of bursts in unshielded ion-chambers. Plotted in the conventional double logarithmic manner, this curve seemed to pass remarkably suddenly from a steep branch of bursts presumably chiefly of one kind to a much less steep branch of bursts presumably of another kind. These branches had been interpreted by Euler[31] as due respectively to single protons from the local stars and to extensive air showers. The assumption of single long-range alpha particles from stars as well as single protons for the analysis made in 1948[30] was criticized by Fujimoto and Yamaguchi[32]; and the experiments of Bridge, Hazen, Rossi, and Williams[19] showed that there was a significant contribution to the bursts from the individual stars occurring within the ion-chamber. In the present work, the sharpness of the kink between the two branches has been confirmed and a satisfactory interpretation is given involving star processes rather than single high-energy alpha particles. In addition a component of smaller bursts evidently caused by single long-range protons has been found and the smallest bursts can be reliably attributed to the known numbers of single mesons and single electrons that intersect the ion-chamber.

* These measurements were reported at the Chicago meeting of the American Physical Society, November, 1953 [Phys. Rev. **93**, 913(A) (1954)].

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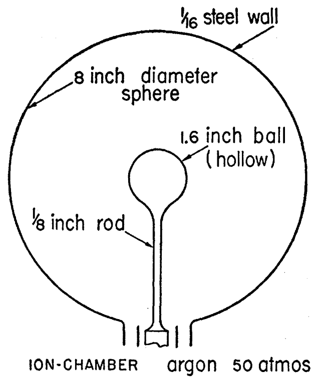

FIG. 1. The 8-inch spherical ion-chamber.

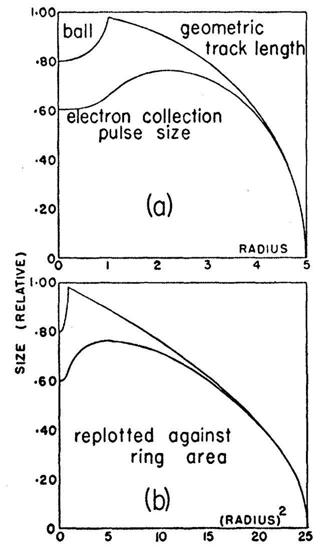

FIG. 2. The relative track lengths in the collecting volume of the ion-chamber for fast particles intersecting the sphere at different radial distances and the corresponding relative sizes of the electron collection pulses under the assumption of uniform ionization along the tracks.

2. ION-CHAMBER DETAILS

Spherical ion-chambers were used in order that the measurements might be as basic as possible and hence of permanent value. Several ion-chambers of diameters 30 inches, 8 inches, and 2 inches were constructed. All had walls of $\frac{1}{16}$-inch thick steel. The collecting electrode was a hollow thin-walled ball, whose diameter in each case was one-fifth that of the ion-chamber, supported on a cylindrical stalk about one-sixtieth of the diameter of the ion-chamber as shown in Fig. 1. Only work with the 8-inch ion-chambers will be dealt with in this paper.

The ion-chambers were free of organic insulating material and were baked at 150°C under vacuum. The filling gas was the best quality (about 99.8% pure) welding argon, the only appreciable impurity being nitrogen, and the pressure in the 8-inch ion-chambers was 50 atmospheres absolute [1 atmos = 14.7 lb in.$^{-2}$ at 0°C]. The effect of further purification with hot calcium was tried with a 30-inch ion-chamber at 10 atmospheres but was found to have little effect. The results obtained with several different samples of the welding argon in the 8-inch ion-chamber were indistinguishable.

The measured pulses arose from electron collection in the ion-chamber and so they did not in general correspond fully in size to the number of ion-pairs produced. For example, a burst of uniform volume ionization in the ion-chamber would give a voltage pulse which was 0.90 of the size which would be obtained if the effect of the positive ions also was included. The diameter of our collector was chosen to make this factor numerically the same as that calculated by Bridge, Hazen, Rossi, and Williams[19] for uniform ionization in their standard cylindrical ion-chamber. When two ion-chambers correspond in this respect, a spherical ion-chamber has an advantage over a cylindrical one in that the collecting field in the sphere varies between the two electrodes only in the ratio 1:25 whereas in the cylinder it changes in the ratio 1:120. The size of the electron pulse for a single uniformly ionizing particle traversing the spherical ion-chamber, as a function of the distance r of the track from the center of the sphere, including the effect of track length as determined by the outer wall and the collector, is shown in Fig. 2(a). This figure may be compared with Fig. 6 of reference 19. In Fig. 2(b) the pulse size has been plotted against the ring area (r^2) at radius r as this gives a more realistic picture for a sphere.

The experimental results cannot be corrected in detail to allow for the loss of pulse size due to electron collection because the correction for a given burst depends upon the unknown configuration, within the ion-chamber, of the ionization that produced it. However, it is possible, when making calculations of the burst sizes produced by the known types of ionizing events, to introduce the exact correction for this effect. Therefore the experimental results will be presented without correction, in terms of the number of ion-pairs actually *detected*, and it will be understood that a correction should be incorporated in any calculations that are made. An approximate correction of the experimental data for the missing contribution from the positive ions can be made by increasing the size of all bursts by 11%.

3. RECORDING EQUIPMENT

Two completely independent measuring systems were used, one with a vibrating reed electrometer and the other with a Raytheon CK-5889 electrometer tube. In both systems the feedback circuit consisted of an air dielectric capacitor in parallel with a 10^{10}-ohm resistor. The value of the capacitor was about 10 $\mu\mu$f in the vibrating reed instrument and 8 $\mu\mu$f with the electrometer tube circuit. The time constants of the circuits were therefore each about 0.1 sec.

The vibrating reed electrometer was set at unity gain (full scale 1 volt) so that it was used essentially as an impedance converter only. This setting gave the shortest rise time of the output pulses. Two feedback dc amplifiers of different sensitivity were connected in parallel to the output and used to drive the two pens of

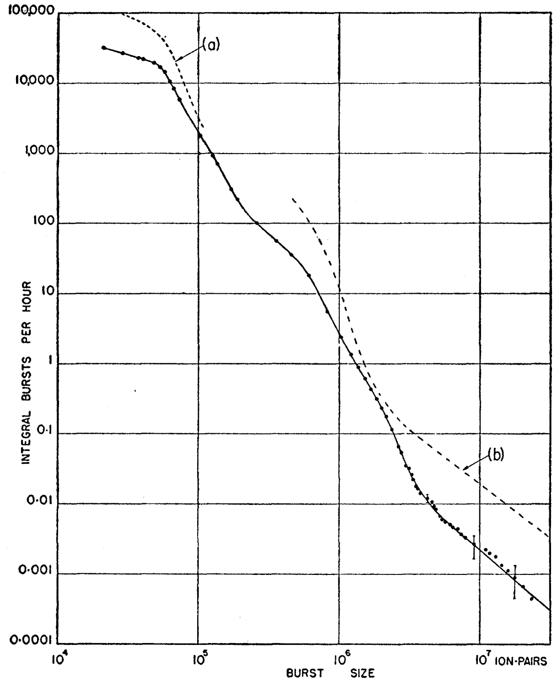

FIG. 3. The size-frequency integral distribution of the bursts in the unshielded 8-inch spherical ion-chamber, filled with argon at 50 atmospheres. (a) The effect of a very small source of radium gamma rays; (b) the curve measured[29] in 1939 with a different ion-chamber under a heavy roof.

a fast (Brush Development Company) oscillograph. The ratio of the sensitivities was 20:1. The lengths of the pulses on the oscillograph paper were measured visually and counted. An electronic pulse height analyzer also was used for the smaller bursts, thus extending the measurable size range, but measurement of very small bursts with the vibrating reed electrometer was found to be unreliable since these pulses were swamped by the residual hum and the 400-cycle carrier from the synchronous rectifier. With the vibrating reed apparatus the range of size measured reliably was about 400:1.

The pen records were indispensable because they enabled the onset of a circuit failure, or other spurious effect such as a momentary failure of the mains, to be recognized and allowed for in the results. A substantial portion of the size-frequency distribution curve at the large size end is composed of bursts which occur less than once in 100 hours: even a few unrecognized large spurious pulses would seriously alter the shape of the curve at this end.

In the electrometer tube apparatus, which was a later development, paper recording for the larger pulses and dc coupling in one pen channel were preserved. The other pen (the more sensitive one) was driven through a pulse lengthener from a gating circuit which opened only when the rate of increase of current in the ion-chamber exceeded a preset amount. This permitted the pen pulses to rise from a steady base line allowing easy and accurate measurement. In addition to the two recording oscillographs used for the larger pulses, a ten-channel pulse-height analyzer was used for the intermediate sizes and, for measuring the smallest pulses, a discriminator and decade scaler. In this way the size range measurable was extended to 4000:1.

The length of the gate was about one millisecond for the smallest pulses and increased slightly with pulse height. For electronic measurement, the pulse was differentiated and the derived pulse arising from the closing of the gate was fed to the discriminators. This pulse was of definite shape and of polarity opposite to that of the original pulse.

It will be appreciated that exceedingly stable and reliable apparatus is required for measuring bursts, especially at sea level where measurements may require several years' time. The slope of the size-frequency distribution curve in places is very steep (the power law exponent approaches 5), so that even relatively small spurious variations in the measured sizes of the bursts will tend to flatten out the steeper parts of the curve. In this respect, the vibrating reed electrometer was found to be not entirely satisfactory. This instrument is noted for its extremely good stability in dc measurements, but when applied to record pulses with a rise time less than 0.05 second the band width or damping becomes important and this changes as the tubes age. It was found necessary in the present work to readjust the vibrating reed instrument about once a month.

4. CALIBRATION

The apparatus was calibrated by applying a square wave of known amplitude to a small (1.6 $\mu\mu$f) condenser connected to the input of the amplifier or by applying similar pulses directly to the insulated outer electrode of the ion-chamber after removing the ion-collecting voltage. The pulse frequency was sufficiently low to allow the pens to return to zero between successive deflections. The pulse height analyzer and the decade scaler were also calibrated by this method, using the criterion that at the correct amplitude a count would be registered for every second pulse on the average. These calibrations were made over the whole range of pulse size about once every 3 days. The capacities of the small condenser and of the ion-chamber were measured by means of a standarized *in situ*[33] bridge so that the apparent burst sizes are known absolutely in ion-pairs to about $\pm 2\%$. It was found (where the results were statistically adequate) that the size-frequency distribution curves obtained with the vibrating reed apparatus and with the electrometer tube apparatus, with separate ion-chambers and gas fillings, coincided to within this accuracy. However, small bursts registered by the vibrating reed near its limit of detection appeared to be too numerous and have not been included in the results.

[33] British Ref. AM 10SB/253.

5. RESULTS

The ionization bursts observed in the unshielded 8-inch ion-chamber (volume 4.4 liters, with 50 atmos argon at 0°C) at 400 feet above sea level at Deep River, Ontario, (Lat 46°06′N, Long 70°30′W) are shown in Fig. 3. For convenient replotting, the coordinates of representative points on the curve are given in the first two columns of Table I. The burst size, in ion-pairs, is the measured size resulting from collection of the electrons only.

In the region of the larger bursts, 10^6 ion-pairs and upwards, the results from the vibrating reed and from the electrometer tube apparatus were essentially identical and have been added together to make a total of 4483.5 hours of running time. The curve has been plotted nearly to the largest burst observed (5.3×10^7 ion-pairs) and the statistical errors are indicated at representative points. The marked kink at the level of one burst in 100 hours (and at burst size 5×10^6 ion-pairs) is real and similar to the discontinuity first reported in 1939.[29] One of the 1939 curves is shown, as broken curve (b), in Fig. 3. This curve was obtained with an ion-chamber containing approximately the same mass of argon, but the ion-chamber was large (175 liters), the gas pressure low (1.52 atmospheres), and the ion-chamber was in a laboratory with a thick roof. If one considers these differences, the two curves are reasonably similar. The larger size of the bursts in the lower branch of the older curve may be attributed to the heavy roof. The observation of a similar discontinuity has been mentioned by Prescott.[34]

The curve between 2×10^4 and 10^6 ion-pairs contains only results obtained with the electrometer tube apparatus. As already mentioned, in the region of smaller bursts, between 10^5 and 10^6 ion-pairs, the results from the vibrating reed and the electrometer tube apparatus differed and bursts of less than 10^5 ion-pairs could be measured only with the latter.

It will be seen from Fig. 3 that the inclusion of bursts of smaller size than were measured previously has revealed some new features in the size-frequency distribution curve. There is a knee near 20 000 bursts per hour above which the curve levels off. There is a well-marked bump just above the 10 bursts per hour level, and a less pronounced convexity between one burst in 100 hours and one burst per hour—just above the kink.

All these measurements were made with the apparatus inside a large wooden laboratory maintained at constant temperature. An additional run of 100 hours was made with the electrometer tube ion-chamber outside on the roof in the free atmosphere, the preamplifier being connected by a long cable to the main amplifier inside the building. The preamplifier was insensitive to temperature variations. During this 100-hour period the barometer was continuously near 997 millibars, the average for the station. The experimental points from this relatively short run did not differ significantly from the curve of Fig. 3, showing that at least for the smaller size bursts in the unshielded ion-chamber the walls of the laboratory had a negligible effect. (On the other hand, when the ion-chamber was shielded with small thicknesses of lead, there was a difference between the rates obtained inside and outside the building.)

Barometer effect corrections of -3% per cm Hg for bursts of less than 10^5 ion-pairs and -10% per cm Hg for all larger bursts appeared to be suitable and were applied but the running time was so long that these corrections had negligible effect and might have been omitted.

[34] J. R. Prescott, Proc. Phys. Soc. (London) **65**, 925 (1952).

TABLE I. The size-frequency integral distribution of bursts in the unshielded 8-inch ion-chamber.

$\log_{10}$ (size in ion-pairs)	$\log_{10}$ (No./hr larger than given size) All bursts	Extensive showers	Stars	Single protons	Single mesons	Electrons
4.3	4.52	1.51	1.25	2.70	4.33	4.04
4.4	4.46	1.47	1.25	2.68	4.29	3.93
4.5	4.41	1.42	1.24	2.66	4.25	3.88
4.6	4.35	1.37	1.23	2.64	4.19	3.81
4.7	4.28	1.29	1.22	2.62	4.12	3.74
4.8	4.02	1.15	1.21	2.58	3.85	3.47
4.9	3.66	0.98	1.19	2.51	3.43	3.18
5.0	3.32	0.81	1.17	2.41	3.06	2.81
5.1	2.98	0.64	1.15	2.29	2.68	2.40
5.2	2.62	0.46	1.11	2.15	2.26	1.91
5.3	2.27	0.29	1.07	2.00	1.79	1.10
5.4	2.04	0.11	1.02	1.88	1.32	0.01
5.5	1.85	$\bar{1}.94$	0.96	1.74	0.81	...
5.6	1.67	$\bar{1}.76$	0.87	1.56	0.35	
5.7	1.47	$\bar{1}.59$	0.77	1.36	...	
5.8	1.21	$\bar{1}.42$	0.64	1.06		
5.9	0.80	$\bar{1}.24$	0.48	0.50		
6.0	0.43	$\bar{1}.07$	0.28	$\bar{1}.83$		
6.1	0.08	$\bar{2}.90$	0.02	$\bar{2}.88$		
6.2	$\bar{1}.74$	$\bar{2}.72$	$\bar{1}.69$	...		
6.3	$\bar{1}.39$	$\bar{2}.55$	$\bar{1}.29$			
6.4	$\bar{2}.94$	$\bar{2}.38$	$\bar{2}.79$			
6.5	$\bar{2}.47$	$\bar{2}.21$	$\bar{2}.14$			
6.6	$\bar{2}.11$	$\bar{2}.03$	$\bar{3}.31$			
6.7	$\bar{3}.88$	$\bar{3}.86$	$\bar{4}.32$			
6.8	$\bar{3}.69$	$\bar{3}.69$	...			
6.9	$\bar{3}.52$	$\bar{3}.52$				
7.0	$\bar{3}.34$	$\bar{3}.34$				
7.5	$\bar{4}.47$	$\bar{4}.47$				

6. BACKGROUND FROM NATURAL GAMMA AND ALPHA RADIATIONS

The laboratory used for these measurements was built upon a thick layer of white crystalline dolomite which shielded it from the natural gamma radiation from the subsoil and the building materials were selected for their low radioactive content. The small bursts due to the gamma radiation from a watch dial placed near the ion-chamber produced the effect shown by the broken curve (a) in Fig. 3, but the intensity of this gamma radiation was shown, by means of a scintillation detector, to be about 100 times the intensity of the natural gamma radiation in the laboratory. It was therefore concluded that the effect of the natural gamma radiation was negligible. The bursts arising from the natural alpha particles in the ion-chamber were also shown to be negligible by measuring background with low-pressure argon in the ion-chamber.

7. COMPONENTS OF THE DISTRIBUTION CURVE

The size-frequency distribution curve of Fig. 3 was analyzed, by a procedure which will be described in the following two sections, into components attributed to five different burst-producing agents: μ mesons, electrons, protons, stars, and extensive showers. These components are shown in Fig. 4 and given in the remaining columns of Table I. The sum of the smoothed component curves agrees with the experimental curve to within $\pm 2\%$, but, of course, this does not mean that any component is established with comparable accuracy except over a small region of burst size where it happens to be the principal component. It may be worth mentioning that the diameters of the experimental point marks in Fig. 3 correspond to a change of rate of 10%. We shall next describe the subsidiary experiments, and the calculations and assumptions, on which the analysis was based.

8. SUBSIDIARY EXPERIMENTS

(a) Bursts under 27 cm of Lead

The integral distribution of bursts measured (1852 hours) with the 8-inch ion-chamber shielded by a hemisphere of lead, 27 cm thick, is given in Fig. 5. This experiment formed part of a study of the effect of lead shields of different thicknesses which will be published in another paper.

Under such a great thickness of lead it is not expected that the soft electronic components of the cosmic radiation in air will produce any effect. The bursts observed will be due to the μ mesons and the protons that penetrate the lead, to electronic cascades originating in the lead, and to star production near or within the ion-chamber.

Referring to Fig. 5, and neglecting at this stage the component labeled "stars," it can be seen how it was possible to make a first approximate analysis into meson, proton, and electronic cascade components by assuming that the latter distribution was a power law consistent with the measured size-frequency distribution for the bursts of sizes greater than 10^6 ion-pairs. A straight line representing this power law was extended beyond 10^5 ion-pairs and subtracted from the main curve. The integral size-frequency distribution of the larger proton bursts thus obtained was then also extrapolated towards smaller sizes in a smooth reasonable manner to produce a total rate of proton bursts equal to about 0.5% of the rate for bursts of all kinds. Both the proton and the electronic cascade bursts were now subtracted from the main curve and this left the distribution of bursts which has been ascribed to single μ mesons. This distribution had a very steep and approximately straight (power law) tail which seemed to be reasonable (see Sec. 10 below).

(b) The Extensive Air Showers

An 8-inch ion-chamber was used in coincidence with a 30-inch ion-chamber placed at the same level about 3 meters away, coincidences being established by means of the electronic gating circuit associated with the electrometer tube recording equipment. Only those bursts in the 8-inch ion-chamber which were associated with pulses larger than a certain minimum size in the 30-inch ion-chamber were recorded. The minimum size chosen corresponded to intersection of the 30-inch ion-chamber by at least four extensive shower particles. Since the 30-inch ion-chamber was 14 times the area of the 8-inch ion-chamber, this ensured that while most of the extensive showers would be detected in the 8-inch ion-chamber, a negligible number of accidental coincidences due to unnecessarily frequent opening of the gate would occur. The experimental points obtained are shown on Fig. 4 and they appear to be in line with the lower branch of the unshielded distribution curve. The alignment indicates that the lower branch contains only bursts due to extensive showers. The complete distribution of bursts due to extensive showers in the

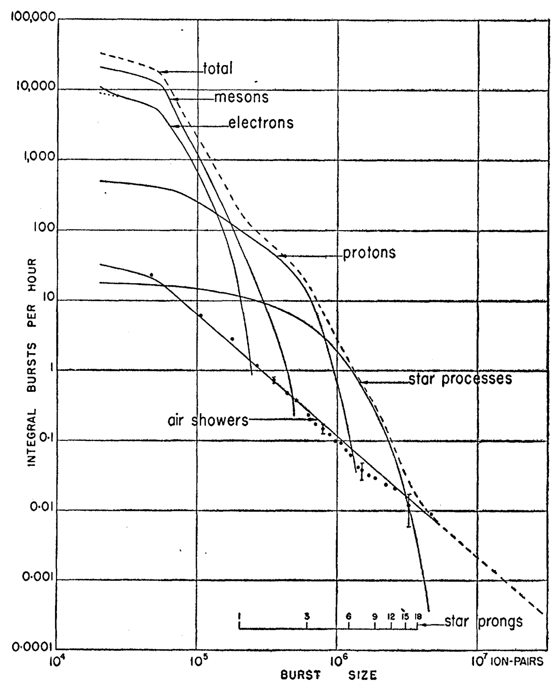

FIG. 4. The five components of the size-frequency integral distribution. The experimental points are from a coincidence experiment to determine the bursts due to extensive air showers. The scale of star prongs is from the prong frequency distribution found in photographic emulsions.

unshielded 8-inch ion-chamber may be represented by the power law,

$$N=6.45S^{-1.73}, \quad (1)$$

where N is the number of bursts per hour of size equal to and greater than S in units of 10^5 ion-pairs.

(c) Preliminary Analysis of the Unshielded Distribution

A first approximation to the analysis of the unshielded distribution curve was then made using the measured bursts due to the extensive showers, proton bursts with the same distribution as those found under thick lead but with their rate of occurrence normalized to produce the "proton bump," and meson bursts, derived from the distribution found under thick lead by assuming an absorption coefficient in lead, 0.038×10^{-2} g^{-1} cm^2, equal to that measured by Kraushaar[35] for mesons of range less than 300 g cm^{-2}. When all these bursts were subtracted from the main curve two other components appeared. One of these was similar to the distribution of bursts from single mesons and was attributed to single electrons. The other was composed of bursts extending in size beyond the proton distribution but with a rather sharply defined limit at the kink. These are the bursts which, on account of their apparently sharply limited size at about four times the size of the largest proton bursts, were previously attributed[30] by one of us (H.C.) to alpha particles from stars. However, it has now been realized that these bursts can very well be represented by an exponential size-frequency distribution and still retain, on the conventional logarithmic plot, their apparently sharply limited size. Further, it is known from measurements in photographic emulsions that the frequency distribution of stars is approximately exponential in terms of their number of prongs. This component has therefore been attributed to stars originating in the ion-chamber and in its walls.

Confirmation that this identification is valid may be obtained from star measurements in photographic emulsions. The distribution of bursts attributed to stars in Fig. 4 results from the final analysis, described in Sec. 9 below, in which it was assumed only (with complete success) that the distribution was exponential. Collected data of the relative abundance in photographic emulsions of stars with different numbers of prongs have been plotted by Rossi,[36] showing a number of distributions approximately exponential in terms of the number of prongs. These distributions tend to become steeper at low altitudes. A distribution for sea level is not given, but it seems reasonable to assume that at sea level the distribution is an exponential in which there are 300 times as many stars with 3 prongs as there are stars with 15 prongs. If this distribution is fitted to the exponential

[35] W. L. Kraushaar, Phys. Rev. **76**, 1045 (1949).
[36] B. Rossi in Proceedings of the *Echo Lake Cosmic-Ray Symposium* (Office of Naval Research, Washington, D. C., 1949), p. 335.

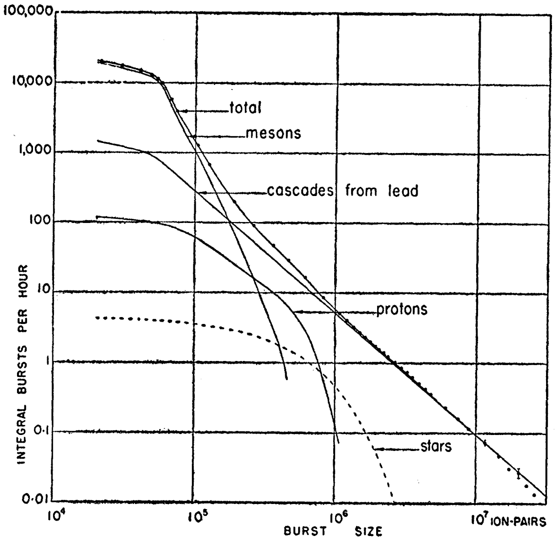

FIG. 5. The size-frequency integral distribution of the bursts in the 8-inch spherical ion-chamber filled with argon at 50 atmospheres and shielded by a hemisphere of lead, 27 cm thick. Also the four components of the size-frequency distribution under lead.

in Fig. 4, it yields the scale of prong numbers shown inset. It follows that each star prong produces on the average 2.0×10^5 ion-pairs corresponding to an energy of 5 Mev. The average energy per prong found for stars of less than 10 prongs in photographic emulsions, is a little larger than this[37]—about 8 Mev for the shorter proton prongs and 15 Mev for alpha-particle prongs. The difference may indicate that there is some columnar recombination in the ion-chamber, tending to diminish the number of ion-pairs collected from heavily ionizing star prongs.

Further confirmation comes from the remarkable observations of stars in argon (and other gases) made by Brown[38] using a combined cloud and ionization chamber. Brown finds 8.9 ± 0.6 stars of all sizes (including single prong stars) per gram atomic weight of argon at 10 600 feet altitude and he gives an experimentally determined factor of 12.5 ± 1.0 between the sea level and 10 600 feet rates which yields 0.71 star per gram atom per hour in argon at sea level. From Fig. 4, after dividing by 9.75, the number of gram atoms of argon in the ion-chamber, the number of star bursts with one or more prongs is found to be 1.20 per gram atom per hour which is in quite good agreement. However, it is profitable to make a detailed comparison of Brown's sea level figures with ours. This is done in Fig. 6, where the exponential curve is replotted from Fig. 4 and the experimental points are obtained from the figures in Table II of Brown's paper. The exponential is

$$N=1.89e^{-0.455P}, \quad (2)$$

[37] Harding, Lattimore, and Perkins, Proc. Roy. Soc. (London) **A196**, 325 (1949).
[38] W. W. Brown, Phys. Rev. **93**, 528 (1954).

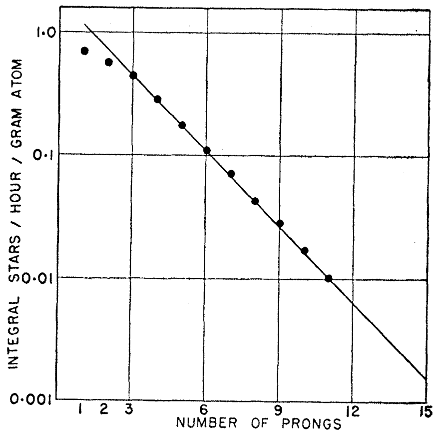

FIG. 6. The solid line is the star frequency integral distribution replotted from Fig. 4. The points are from the cloud chamber observations of stars in argon at sea level, made by Brown.[38] Note the deviation for single- and double-prong stars.

where N is the number of stars, per hour per gram atom of argon, with P or more prongs. It is seen that the two sets of measurements appear to be in exact agreement except for a deviation in Brown's data for the double- and single-prong stars. This deviation may reasonably be attributed to the triggering level of 8 Mev used by Brown. He says "the true flux may be still higher . . . since interactions in which less than 8 Mev . . . is dissipated . . . are not counted."

(d) Identification of Proton Bursts

The 8-inch ion-chamber was placed beneath a Lucite heavy-particle-selecting Čerenkov detector[39] as shown in Fig. 7. This apparatus was kindly lent to us by Dr. M. Bercovitch of this laboratory. Three Geiger counter trays in coincidence, one above and two beneath the Čerenkov detector, selected ionizing particles which could intersect the ion-chamber. The Čerenkov detector was put in anticoincidence with these Geiger coincidences so that only particles that produced no appreciable amount of Čerenkov light were used to gate the ion-chamber. It is known[39] that such particles are mainly single protons, and with a Lucite detector they range in energy up to about 320 Mev.

The size-frequency distribution of the bursts selected in this way should correspond to that of all the long-range protons in the same energy range that intersect the ion-chamber, but of course the selected bursts will be very much less frequent. The largest bursts should correspond to the protons that cross the gas volume near the end of their range, and there should be a cutoff of the smaller bursts corresponding to the 320-Mev energy limit of the protons selected by the detector, i.e., at rather less than twice minimum ionization. The bursts from single slow mesons in this experiment were calculated and shown to be entirely negligible both in size and frequency.

The experimental points obtained in a run of 180 hours duration normalized at a point near 2×10^5 ion-pairs to the so-called proton component of the unshielded ion-chamber are shown in Fig. 8. It is evident that the fit supports the identification of this component as due to protons.

9. FINAL ANALYSIS OF THE DISTRIBUTION CURVE

The μ meson, electron, proton, star, and electronic cascade components, which had been found, were then readjusted so as to produce by successive approximation a consistent analysis of both the unshielded and the 27-cm lead distribution curves. The following conditions were imposed:

(a) The bursts from electronic cascades generated in thick lead have a power-law integral size-frequency distribution with exponent -1.73 ± 0.01, consistent with the slope used in the preliminary analysis of Fig. 5.

(b) The bursts in the unshielded ion-chamber from extensive air showers have a power-law integral size-frequency distribution with exponent -1.73 ± 0.01, as measured in the coincidence experiment.[40]

(c) The bursts from single μ mesons have the same size-frequency distribution (i.e., only the rates differ and by the same factor for all sizes) in the unshielded and shielded ion-chambers and their absorption coefficient is 0.038×10^{-2} g^{-1} cm^2 of lead.

(d) The bursts from individual electrons are found only in the unshielded ion-chamber.

(e) The bursts from stars have the same size-frequency distribution in the unshielded and shielded ion-chambers and their integral rate is an exponential function of their size.

(f) The bursts from protons have the same size-frequency distribution in the unshielded and shielded

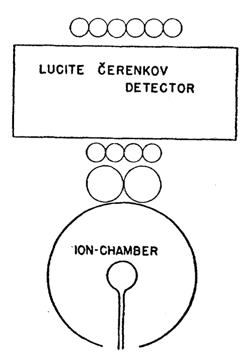

FIG. 7. The experimental arrangement for isolating bursts due to long-range protons. The sensitive areas of the counter trays of the 3-fold coincidence telescope were approximately square.

[39] T. Duerden and B. Hyams, Phil. Mag. 43, 717 (1952).

[40] The equality of the exponents in (a) and (b) is an experimental result which may be significant, but it must be noted that the value for the unshielded ion-chamber depends upon the material and the thickness of the wall. The exponent is considerably smaller with a thin shield of lead above the ion-chamber. It is possible that 1.73 is the limiting value reached as the wall thickness approaches zero.

ion-chambers, and the shape is as similar as possible to that of the Čerenkov experiment curve.

(g) The absorption in lead of the bursts from stars is the same as that of the bursts from protons.

The result of this analysis has already been given in Fig. 4 and in Table I.

The absorption coefficient found for the protons in this analysis was $(4.7\pm0.6)\times10^{-3}$ g^{-1} cm^2 in Pb. This figure is not dependent only upon the unshielded and the 27-cm shield data. When the same value was used for analysis of the bursts measured under 12-, 17-, and 22-cm shields, consistent results were obtained. The corresponding mean free path is 215 ± 30 g cm^{-2}. The difficulties encountered by others especially at sea level (see for example Bridge and Rediker[41]), in attempting to measure the absorption of the nucleonic component in lead in the presence of the background of showers from electronic cascades, do not affect the present experiment where the result depends upon direct detection of the slow protons. The value obtained agrees with that found by Millar *et al.*,[42] 206 ± 30 g cm^{-2}, using a cloud chamber in which the protons were observed directly.

The absorption of the bursts from electronic cascades between 12 and 27 cm of lead is exceedingly small corresponding to a mean free path in excess of 2000 g cm^{-2}. This indicates, unless there are two compensating processes at work, that these cascades are produced mainly from mesons. The analysis of the data does not actually give any information about the absorption of the star-producing agents, condition (g) above. Under thick lead, the star bursts are swamped by the electronic cascade bursts. With very thin lead shields (less than 0.5 cm), there is some evidence of a transition effect in the star production but the absorption of the proton component shows no transition effect. The bursts measured under lead will be treated more fully in another paper.

10. CALCULATION OF BURSTS FORM SINGLE MESONS

The flux of cosmic-ray particles and showers at sea level is known from measurements that have been made with Geiger counters. The omnidirectional flux through a sphere of unit cross-sectional area is given[43] as 2.41 $\times10^{-2}$ per sec unshielded and 1.68×10^{-2} per sec with 167 g cm^{-2} of lead between the counters. The latter rate arises almost entirely from μ mesons and is readily extrapolated to 27 cm of lead [see Sec. 9(c)]. The corresponding rates for an 8-inch sphere are 28 100 per hour unshielded and 18 600 per hour shielded by 27 cm of lead. It is satisfactory that the rates actually measured are in fair agreement with those figures, especially as the measured rate of the smallest bursts was found to be rather variable and somewhat affected by the setting used for the trigger of the gating circuit.

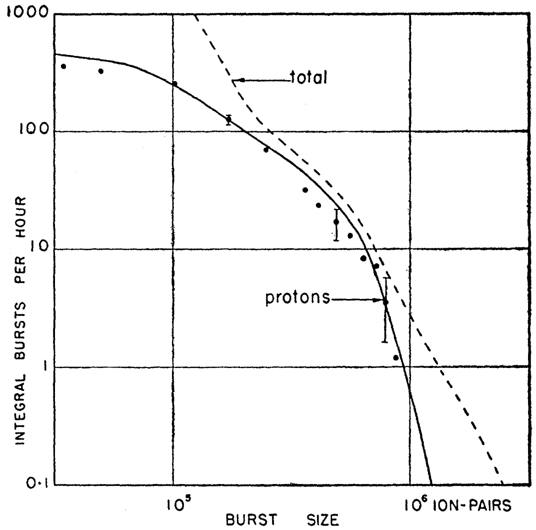

FIG. 8. Comparison of the integral distribution of proton bursts (experimental points) selected by the Čerenkov detector with the proton component (full curve) of Fig. 4. The two rates have been normalized at the fourth experimental point near the size 2×10^5 ion-pairs.

The size-frequency distribution of bursts expected from single mesons of energy 1 Bev in the 8-inch ion-chamber was considered by Gardner.[44] He used the energy loss and its fluctuations due to the Landau effect,[45] as given by Symon,[46] the distribution of path lengths in the ion-chamber as determined by the inner and the outer spheres, and a detailed treatment of the loss of pulse size due to the electron collection characteristics of the ion-chamber. Two limiting cases were considered. In one it was assumed that all the energy lost by the meson appeared as ionization in the ion-chamber, and in the other, following Hudson and Hofstadter,[47] that the larger energy losses (which are presumably the production of single energetic delta rays) expend only a limited amount of their energy in the ion-chamber. In the latter case the Landau fluctuations are cut off at a size that roughly corresponds to the ionization of the meson and one delta ray crossing the ion-chamber.

Gardner's curves are compared with the experimental distribution curve of mesons under 27 cm of lead in Fig. 9. The calculated energy loss was converted to number of ion-pairs by assuming that one ion-pair corresponded to 25.4 ev,[48] and the integral rate was

[41] H. S. Bridge and R. H. Rediker, Phys Rev. **88**, 206 (1952).
[42] Millar, Henderson, Garrison, Potter, Sandstrom, and Todd, Phys. Rev. **94**, 167 (1954).
[43] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).
[44] J. W. Gardner, Atomic Energy of Canada Limited Report, CRT-565, 1954 (unpublished).
[45] L. D. Landau, J. Phys. (U.S.S.R.) **8**, 201 (1944).
[46] K. R. Symon, Harvard University thesis, 1948 (unpublished).
[47] A. M. Hudson and R. Hofstadter, Phys. Rev. **88**, 589 (1952).
[48] Rutherford, Chadwick, and Ellis, *Radiations from Radioactive Substances* (Cambridge University Press, Cambridge, 1951, second edition, p. 81. It would have been more correct to have used the recent value 26.4 given by P. Jesse and J. Sadauskis, Phys. Rev. **90**, 1120 (1953).

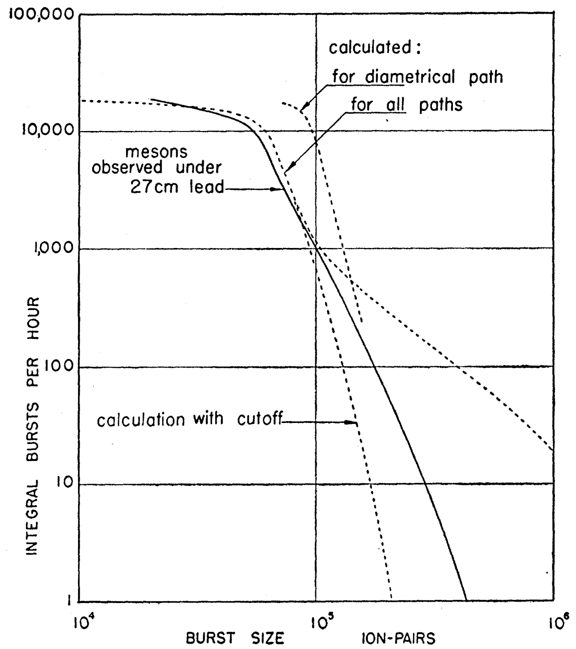

FIG. 9. The broken curves are size-frequency integral distributions calculated by Gardner[44] for the bursts produced by single μ mesons of energy 1 Bev in the 8-inch ion-chamber. These distributions have been normalized to the known omnidirectional flux of mesons under 27 cm of lead at sea level. The full curve is the completely independent size-frequency distribution measured with the 8-inch ion-chamber shielded by 27 cm of lead.

normalized to the Geiger counter rate of 18 600 bursts per hour. The agreement between the calculated and the experimental curves, considering that they have not been fitted in any way, is good—they diverge only for the larger sizes where the calculation gives alternative results. The experimental curve lies between the two calculated curves but is much nearer to the calculation with cutoff of the energy losses. The possibility of folding the meson spectrum into Gardner's calculation was investigated to see if inclusion of the larger bursts obtainable from mesons near the end of their range would improve the agreement, but it appeared that an insufficient number of suitable bursts was to be obtained in this way. It may be concluded that a cutoff is necessary but that the one used was slightly too severe.

Also shown in Fig. 9 is a distribution curve for mesons crossing the ion-chamber diametrically. In this curve, the Landau fluctuations alone (with cutoff) provide the spread in size. Comparison with the fully calculated distribution curve shows the influence of the ion-chamber geometry.

The calculated argon curve with no energy loss cutoff has a tail which is sensibly parallel to the power-law distribution of the electronic cascade bursts found under thick lead up to 10^6 ion-pairs where a 1-Bev meson begins to have insufficient energy to maintain the tail. This is indicative of the well-known process by which the knock-on electrons from mesons in the lead produce bursts in the ion-chamber after the electrons have cascaded in the lead.

The remaining component of the unshielded distribution, attributed to electrons, and the electronic cascade bursts from lead will be discussed in another paper when the observations made with various thicknesses of lead shielding are presented.

11. SUMMARY AND CONCLUSION

In the above, the term ionization burst, usually applicable to the larger cosmic-ray effects in ion-chambers, has been extended to include any detectable pulse and it has been shown that the measured bursts include those produced by single particles of minimum ionization. Though these are easily measured with scintillation counters and proportional counters, they have not hitherto been reliably detected with a continuously sensitive ion-chamber.

The main purpose of this paper is to present what we believe to be rather comprehensive and reliable measurements of the bursts in a particular ion-chamber. The analysis of the bursts into five different components, ascribed to extensive air showers, stars, single protons, single μ mesons, and electrons, is provisional only and not very exhaustive, but it may help to suggest how the data can be interpreted and used. It will be understood that these five components emerge only because of the comparatively large rates of occurrence of the events to which they have been ascribed. For example, it is known, from coincidence experiments not mentioned above, that the single-proton component actually contains an appreciable percentage of multiple events.

12. ACKNOWLEDGMENTS

We wish to express our appreciation of the very careful measurements of the pen recordings carried out by Miss Marjorie M. Hughes. We thank J. W. Gardner for his calculations of meson bursts in our ion-chamber and also E. P. Hincks for a discussion of the manuscript.