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The Three Types of Cosmic-Ray Fluctuations and Their Significance

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A theory of cosmic-ray bursts is advanced with which the energy released in them is assumed to come not from the cosmic-rays themselves but from the battery which charges the electroscope. These bursts then represent, according to this theory, instrumental accidents which must be eliminated before the remaining fluctuations can be interpreted. The discovery that the remainder of the ionization observed in a cosmic-ray electroscope is due wholly to positrons and negatrons shooting through the chamber makes it possible to compute the fluctuations to be expected from a random distribution of these electron shots. The observed fluctuations, after the elimination of bursts, are found to be somewhat larger than the fluctuations thus computed. From the amount of this excess the percentage of cosmic-ray "showers" (two or more associated tracks) can be computed and is found by Evans and Neher to be in general agreement with the number directly observed in cloud-chamber experiments.

FOR the past six years, Millikan has been accumulating a large amount of data on cosmic-ray fluctuations as revealed by measurements made at high and low altitudes with a spherical electroscope 15 cm in diameter and about 1600 cc in capacity, visually observed, and Millikan and Neher have during the past two years used in similar observations a similar self-recording instrument, the records of which are now capable of statistical study.

However, a knowledge of the mechanism by which the ions are produced in such an electroscope has been necessary before an intelligent analysis of the accumulated data could be made. The first step in this knowledge was taken when in the fall of 1931 Bowen and Millikan[1] proved that in the case of cosmic rays, precisely as in the case of gamma-rays, the immediate agents that do practically all the ionizing are high energy electrons or beta-rays, since otherwise the parallelism which both they and Hoffmann had found to exist between cosmic rays and gamma-rays as a function of pressure was not to be expected.

But, the discovery of the free positive electron or positron by Anderson and the later proof, through the use of the Pasadena high energy measuring apparatus, that the positive particles that appear in a cosmic-ray cloud chamber are practically always positrons, still further simplifies the treatment of cosmic-ray fluctuations. For these fluctuations can now be said, with much assurance, to be due to three causes which we shall describe under the names, (1) bursts, (2) showers and (3) "free-electron shots."

The cloud-chamber experiments carried out at the Norman Bridge Laboratory have now shown that about 88 percent of all the cosmic-ray photographs taken reveal single "electron shots," 10 percent more show double electron shots, or pairs, while the other 2 percent consist of more complicated multiple tracks.

If all of the ionization were due to single elec-

[1] R. A. Millikan and I. S. Bowen, Nature, October 3, 1931; see also R. A. Millikan, Phys. Rev. 39, 397 (1932).

tron shots, positrons or negatrons, the problem of fluctuations could be treated with much assurance and certainty by the Poisson-Bateman theory of random fluctuations in accordance with which if t is the duration of an observation and λ the average rate of appearance of ions in such an interval, so that λt is the average number of ions formed, then the probability P_l that l ions instead of λt ions will appear in that interval is given by:

$$P_l = (\lambda t)^l e^{-\lambda t}/l!$$

Treating the great mass of data which we now have reveals the fact that the observed fluctuations are somewhat larger than those thus computed and this, of course, means that other causes of fluctuations are superposed upon that of the single electron shots since each associated pair of tracks is the equivalent of a single track of double the ionizing power, and such bunching of the ionization must obviously increase the chance of divergence from the mean of the ionization produced by completely randomly distributed shots.

But, there is a further cause of departure from this mean. It is found in a phenomenon first noticed by Hoffmann, and usually known as "Hoffmann bursts." When the visible method of observation is used, one occasionally finds that the total discharge obtained during a period of, say, six hours is perhaps five or even six percent larger than the mean although more than 95 percent of the six hour observations fall within less than 2 percent of the mean; and, when the self-recording method is used the inclined line, the slope of which represents the rate of discharge, occasionally shows a sudden displacement which may correspond to a very sudden loss of charge of the electroscope which in extreme cases indicates the instantaneous loss of as much as a sixth, indeed in one instance a half, of the total charge of the electroscope. Such bursts occur in an electroscope of 15 cm diameter, shielded by 10 cm of lead, not oftener than two or three times a day at sea level, but on Pike's Peak, where the rate of discharge is three times as great, we have sometimes found them occurring three or even four times as frequently, They are found to occur very, very rarely when the electroscope is unshielded, but when it is surrounded with a lead shield 10 cm thick, their frequency is multiplied at least ten times by the shield.

This behavior clearly indicates that these bursts are in some way *conditioned* by the aforementioned showers. If the surrounding matter in which the incoming photons can produce showers is condensed about the electroscope, the center from which a shower starts is, on the average, brought close enough to the electroscope so that from the mere geometry of the situation two or more—sometimes many—of the elements of a shower can enter the electroscope, but if the matter from some point in which the shower starts is spread out to a remote distance from the electroscope, most of the elements of the shower will, or course, escape the electroscope. Reasoning in this way as to the distance from the electroscope of the point within the lead shield from which the showers must start, and assuming that the whole observed ionization within the electroscope is due immediately to the shower itself, Steinke[2] has computed that the total ionization produced in the lead on the way to the electroscope, plus that within the electroscope itself, is so great that the photon, which started off the shower, must have been endowed with an energy of 10^{11} or 10^{12} volts. The fact that no energies greater than about one-hundredth of these amounts have ever been found in our cloud-chamber work, indicates to us that Steinke's assumed mechanism of burst-formation cannot be the correct one.

But, there is a second mode of approach to the problem which fortifies this conclusion. The number of pairs of ions produced by a single cosmic-ray electron-shot traversing the average path which it must traverse in going through our electroscope is very close to 5000. This figure is obtained simply by multiplying the number of ions per cm of path, directly counted by Anderson and Neddermeyer at atmospheric pressure, namely 35, by the length of the average path, namely 10 cm, by the observed multiplying factor, namely 14, of our electroscope when the pressure within it has been raised to 30 atmospheres of air. But, we observed on Pike's Peak in the summer of 1932 one burst which corresponded in ion-pairs produced within our elec-

[2] E. G. Steinke and H. Schindler, Naturwiss. 20, 491 (1932).

troscope to 25,000,000 and very recently in an airplane flight to a height of 21,000 feet we got, when using a 15 cm iron shield, another burst corresponding to 75,000,000 ion-pairs. Dividing 75,000,000 by 5000 shows that to account in Steinke's way for this burst requires that the electroscope be traversed at a single instant by 15,000 electron shots. But, not one-hundredth of this number has ever been observed, nor indeed could any such number be produced by the explosion of any known nucleus since even the uranium nucleus contains but 384 electrons, positive and negative all told. Furthermore, even in dense matter the distance between nuclei is so great relatively to their size that the collaboration of many nuclei is scarcely to be considered.

We think, therefore, that by far the simplest explanation of these bursts is found in the assumption that the energy released in the electroscope by them comes, not from the cosmic rays themselves, but rather from the energy supplied by the battery in charging the electroscope. This amounts in our case to 5 billion (10^9) volt-electrons. The energy released in the largest burst we have ever observed—the one that released the 75,000,000 ion-pairs—is about one-half of this amount. The battery energy is, therefore, amply sufficient to produce the quantity of ions involved.

The mechanism which we suggest to account for these bursts is the following: a cosmic-ray shower produces in one side of the electroscope a large number of ions. This swarm of ions by its motion toward the central electrode causes a concentration of the field near this electrode exactly similar to the concentration of field in the cathode dark space in an ordinary discharge tube. An incipient arc is thus formed (i.e., a multiplication of ions by collision) which discharges a considerable portion of the charge on the electroscope before the field falls so low as to stop further ionization by collision. This theory, then, makes these bursts merely "instrumental accidents" which have little to teach about the mechanism of the ionizing action of the cosmic rays themselves.

Accordingly, for the study of fluctuations, we simply discard all those very infrequent records of electroscope discharge-rates in which such bursts appear, and compute the fluctuations from the slopes of all the discharge-rate lines which reveal only an essentially continuous rate of discharge without noticeable sudden breaks. The fluctuations so obtained are a little larger than those computed from the Poisson-Bateman law and because of this difference yield some indication of the number of showers which must be superposed upon the electron shots to account for them. These indications are in pretty good agreement with the percentage of showers found directly in Anderson's and Neddermyer's studies on cloud-chamber tracks. The character of this agreement is shown in the following paper by Robley Evans and H. Victor Neher.

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