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The Absorption of Cosmic-Ray Showers in Lead

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The absorption in lead of the shower rays which produce the bursts of cosmic-ray ionization is measured by two methods. The first method consists in observing the ionization produced above and below a lead absorber placed across the center of an ionization chamber; the second is to observe the probability that a burst of ionization in a chamber is accompanied by a simultaneous discharge of three Geiger-Müller counters over one of which has been placed an absorber. The results of the two methods are in good accord and may be stated in the form that the probability that a ray of a shower will penetrate a thickness of lead decreases linearly with the thickness, becoming zero at approximately 11 cm. The experiments serve to emphasize again the high energies that are involved in a large shower. The results are applied to observations on the effect of shielding on the ionization observed in the stratosphere.

SINCE the first experiments of Rossi,[1] in 1932, on the measurement by means of Geiger-Müller counters, of the absorption of cosmic-ray showers, many refinements have been made, particularly by H. Geiger[2] and his collaborators and by J. C. Street,[3] which have led to a better understanding of the phenomena involved. However, since these showers occur with a large range of sizes and degrees of complexity, additional information can be obtained by observing the behavior of showers of definite size, as may be done with an ionization chamber, instead of observing only the integrated effect of showers of all sizes, as is done in counter experiments. The experiments here described were begun in collaboration with Professor W. F. G. Swann, and some preliminary reports have been published.[4] The absorption in lead of large showers (of the order of a hundred rays, or more) has been measured by two methods in which the ionization that a shower produces is measured before the shower is absorbed.

FIRST METHOD

The principle of this ionization method is to measure the ionization which a given shower produces before and after passing through a thickness of material. Since, presumably, the ionization which a shower produces is proportional to the number of rays which it contains, the observed difference is a measure of the number of rays which are stopped within the material. To measure this, a large cylindrical ionization chamber, 150 cm high and 90 cm in diameter, was used. The chamber was constructed of welded steel of approximately 18 mm thickness. It was divided into two halves, see

[1] B. Rossi, Zeits. f. Physik **82**, 151 (1933).
[2] H. Geiger and O. Zeiller, Zeits. f. Physik **97**, 300 (1935) and earlier papers.
[3] R. H. Woodward and J. C. Street, Phys. Rev. **47**, 800 (1935) and earlier papers.
[4] W. F. G. Swann and C. G. Montgomery, Phys. Rev. **43**, 782 (1933); **44**, 52 (1933). W. F. G. Swann, "Report on the Work of the Bartol Research Foundation," 1933–1934, J. Frank. Inst. **218**, 173 (1934).

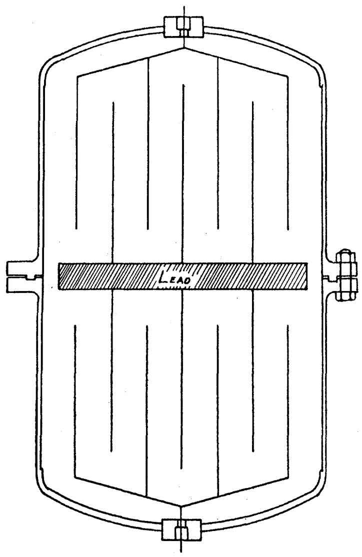

FIG. 1. Diagram of double ionization chamber with absorber in place, showing the electrode arrangement.

Fig. 1, each of 538 liters volume, and each provided with an independent electrode system and guard ring. The electrodes were concentric sheet iron cylinders with conical caps, separated by approximately 10 cm. To collect the ions, the electrodes were maintained at a potential of about 500 volts, and the time of collection of the ions was less than one second. These conditions insure that the statistical fluctuations of the cosmic-ray currents are small.[5] The potential of each electrode system was recorded photographically by allowing the image of an illuminated slit reflected from a galvanometer mirror to fall upon a moving strip of photographic paper. Each galvanometer measured the changes in the plate current of an FP-54 pliotron in the usual manner. The chamber contained nitrogen at 6.8 atmospheres pressure. The capacities of the electrodes were determined by inserting known resistances in the circuits and measuring the time constants of the decay of potential differences between the electrodes. The capacity of each system was found to be about 500 cm.

The thick steel walls of the chamber and the surrounding material served as a source of showers. The ionization which these showers produced was measured in each half of the chamber and the frequency distribution of the shower sizes obtained. Then, to absorb the showers, a circular plate of lead, 7 cm thick and 80 cm in diameter, was inserted between the two halves of the chamber, and the frequency distribution of the sizes of the showers in each half redetermined. Only those showers which produced more than 4×10^6 ions in each half of the chamber were measured. This amount of ionization would be produced by the passage of about 150 high speed electrons through the chamber, if the value for the specific ionization is taken as 60 ions per centimeter.[6] The observations were extended over two 35-hour periods, during each of which more than 200 showers were observed. Since the root-mean-square fluctuation in the cosmic-ray ionization in the time necessary for the galvanometer to deflect was only 6×10^5 ions, the showers of the sizes measured were quite unaffected by these fluctuations. It is of interest to note that the fluctuations in the two halves of the vessel are not statistically independent, but show a correlation caused by the passage of cosmic-ray electrons through both halves. The correlation coefficient is approximately 0.2.[7]

The interpretation of shower observations is complicated by the fact that the showers which emerge from a piece of material are not all of equal size, but are of many sizes whose frequency distribution covers a wide range. In the present experiment, there is the further complication that showers of equal size produce different amounts of ionization, the amounts depending upon their points of origin and their path lengths in the chamber. Thus, we observe three kinds of showers: those which produce amounts of ionization above the limit of measurement in the lower half only, those whose ionizations are above the limit in the top half only, and those which produce measurable amounts of ionization in both halves. Table I gives the numbers of

TABLE I. *Numbers of bursts observed in 35 hours.*

	Both Halves	Upper Half Only	Lower Half Only	Total
Without lead	49	89	78	216
With lead	24	142	102	268

[5] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **47**, 430 (1935).

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

[7] Cf. W. S. Pforte, Zeits. f. Physik **72**, 511 (1931).

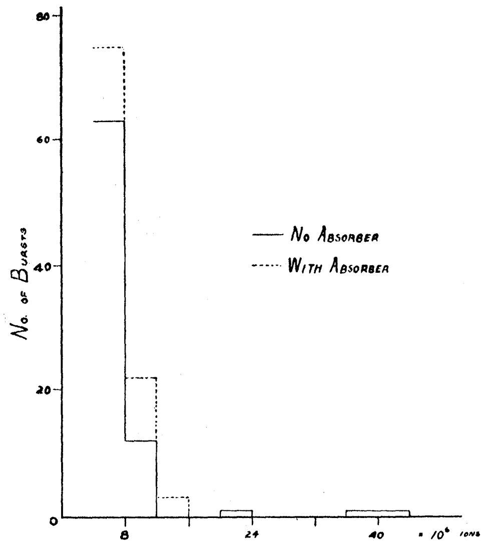

FIG. 2. Frequency distribution of bursts which occurred in the lower half only.

bursts of these three classes observed in 35 hours, with and without a lead absorber.

The effect of introducing the lead is twofold. As well as acting as an absorber of showers produced above it, the lead acts as an additional source of showers. The showers produced in it show themselves most prominently, of course, in the lower half of the chamber. Thus, if we consider the showers which occur in the lower half of the vessel only, we see that more showers are observed with the lead present than without the lead. Fig. 2 shows the distribution in size of the bursts of ionization which occur in the lower half only. However, the difference between the two curves does not represent all the showers which the lead has produced. Certain showers whose points of origin were in the upper half of the chamber but whose sizes, in the absence of the lead, were above the limit of measurement in the lower half only, are now absorbed by the lead and become too small in the lower half to be measured. Therefore, the number of these showers should be added to the difference between the two curves in Fig. 2 to obtain the total number of showers produced by the lead.

The phenomenon in which we are at present most interested is the absorbing effect of the lead upon the showers which pass through it. We see from Table I that the number of showers which produce more than 4×10^6 ions in both the upper and lower halves of the vessel are considerably reduced by the presence of the lead. This reduction in number is to be regarded as the effect of the lead in reducing the size of the showers and making some of them fall below the limit of measurement in the lower half. We may obtain an estimate of the amount of this reduction in size in the following way. Fig. 3 shows the frequency distributions of the ratios of the amounts of ionization produced in the lower half of the vessel to those produced in the upper half by the showers under consideration, with and without the lead absorber. When no lead is present, most of the showers occurring in the upper half of the chamber produce, in the lower half, an amount of ionization only slightly less than in the upper half. This slight difference is to be ascribed to the spreading of the shower rays from their point of origin and their passing out through the side walls of the vessel. When the lead is present, the maximum in the distribution of ratios of sizes shifts to smaller values, since the sizes of the showers in the lower half of the vessel have been reduced without alteration of the sizes in the upper half. We may take the ratio of the positions of the maxima of the two curves as an estimate of the most probable value of the fraction of the rays of a shower which are able to pass through the lead.[8] This value is 0.35/0.85, or 0.4.

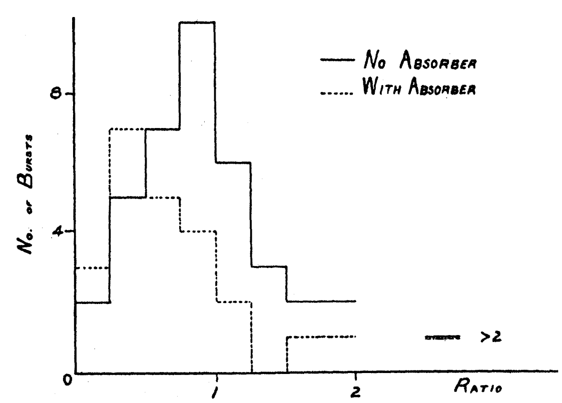

FIG. 3. Frequency distribution of bursts which occurred in both halves of the vessel, with respect to the ratio of the size in the lower half to that in the upper.

[8] It is conceivable that there are showers produced in the lead which proceed upward as well as downward. However, the agreement between the two methods of estimating the absorption in lead indicate that such showers, if present, are relatively few in number.

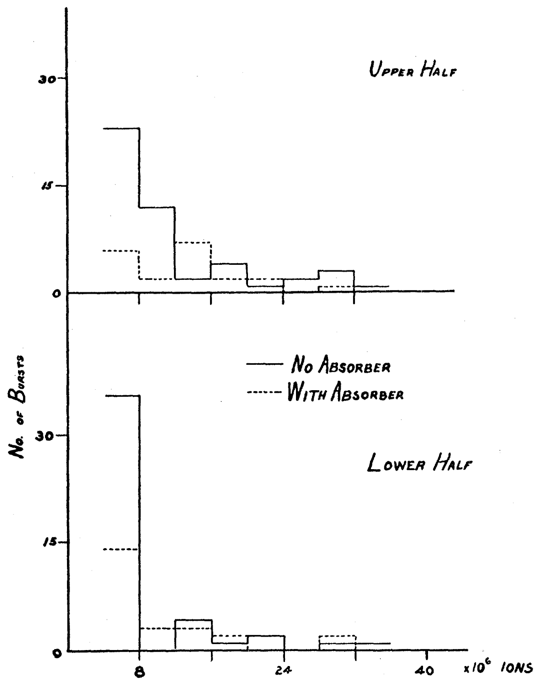

FIG. 4. Frequency distributions of bursts which occurred in both halves of the chamber.

Having obtained a numerical estimate of the reduction which the lead brings about in the size of a shower, we may use it to calculate the number of showers which we should expect to be reduced to a size below the limit of measurement in the lower half of the vessel. This expected reduction, by the lead, of the number of showers which are measurable in both halves of the chamber, may then be compared to the observed reduction. Fig. 4 shows the frequency distribution of the sizes of showers which are above the limit of measurement in both halves of the vessel, with and without the lead present. The lead removes all showers which would have produced less than $4/0.4\times10^6$, or 10×10^6 ions in the lower half of the chamber. Let us take this number of showers to be equal to the number below 10×10^6 ions which *did* occur when no lead was present. This number is 37. The observed decrease is 25. These showers, the bottom components of which have been absorbed, are still observable in the top half of the chamber, and thus the introduction of the lead should cause a corresponding increase in the number of showers observed in the upper half *only*. Fig. 5 shows that there is such an increase and within the limits of the experimental error it is the number expected.

Thus the observations may all be consistently explained if the absorbing effect of the 7 cm of lead is that it reduces the number of rays in a shower passing through it by a factor of 1/0.4. This estimate of the absorbing power of a lead plate may be compared with the absorption effects as measured by a second method, described below.

Second Method

A second method of measuring the absorption in lead of a cosmic-ray shower is based upon measurements of the probability that a shower of a given size will simultaneously discharge several Geiger-Müller counters. In previous papers,[9] it has been shown that, with reasonable assumptions, it is possible to compute and measure this probability. Suppose now that an absorber is interposed between the source of showers and one of the Geiger-Müller counters. The probability that a ray of the shower will set off that counter will then be decreased, and the probability that a ray of the shower can pass through the absorber can be derived. Fig. 6 shows the experimental arrangement used. The source of showers consisted of a tray, L, 41.5 cm square, containing lead shot to a depth equiva-

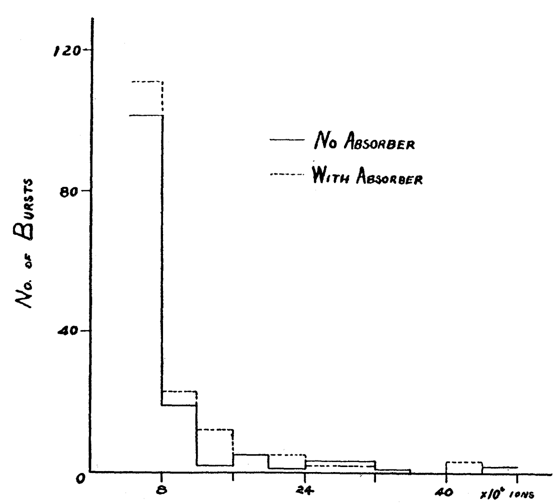

FIG. 5. Frequency distribution of bursts which occurred in the upper half only.

[9] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **48**, 786 (1935); J. Frank. Inst. **221**, 59 (1936).

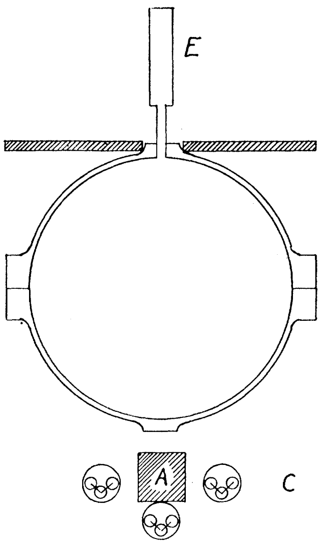

FIG. 6. Experimental arrangement used in the second method.

lent to one centimeter of solid lead. The showers were detected by means of the magnesium ionization chamber, S, and the vacuum tube electrometer, E. The shower rays passing out of the chamber fell upon three Geiger-Müller counters, C, arranged in a "cradle." Over the center counter was placed an absorber, A, of solid lead. A simultaneous discharge of the three counters made an imprint upon the same photographic paper that recorded the bursts of ionization caused by the shower. The fraction of the number of bursts of ionization which were accompanied by a discharge of the set of counters was determined for different thicknesses of the absorber, A. Table II gives the total numbers of bursts of ionization observed in the chamber and the number of bursts with which a simultaneous discharge of the counters occurred. The bursts of ionization are divided, according to size, into five groups. During the course of these observations, the high resistances associated with the counters had two different values. The series of observations labeled I were taken with a lower value of these resistances than the series labeled II. The counter efficiencies in the series I were therefore higher than in II, but the data were treated in such a way, as explained below, that the efficiencies of the counters entered only as a small correction, and the final results are strictly comparable.

The efficiencies of the counters were determined in the usual manner. The counters were arranged so that they formed a telescope pointing in the vertical direction. The number of triple coincidences and the individual counting rates of each counter were measured with and without radium in the vicinity. From these data the recovery time of a counter was computed and hence the efficiency for any given value of the individual counting rate. The efficiency for a counter with no lead over it was 95 percent for the observations in series I, 85 percent in series II.

In order to derive from the above observations a value for the probability that a ray of a shower will penetrate the absorber, we must apply the formulae previously calculated.[9] If N is the number of rays in a shower, p the *a priori* probability that a ray of the shower will pass through a counter in the absence of the absorber, p' the probability that a ray will penetrate the absorber, and E_0 and E_A the efficiencies of a counter without and with an absorber over it respectively, then it can be shown that the probability that the occurrence of a shower will be accompanied by a simultaneous discharge of the three counters is:

$$P=E_0^2E_A[1-2(1-p)^N-(1-pp')^N+(1-2p)^N+2(1-p-pp')^N-(1-2p-pp')^N].$$

For values of N and p which are here under

TABLE II. *Bursts of various sizes observed for different thicknesses of lead absorber.* Rows labeled A give the number of bursts accompanied by counts. Rows labeled B give the total number of bursts.

	Size of Burst ($\times 10^{-6}$ ion pairs)		1.1 to 2.0	2.0 to 3.0	3.0 to 5.0	5.0 to 10.0	10.0 to 20.0
Series I	No Pb	A	117	38	18	16	2
		B	755	105	36	22	3
	2.54 cm Pb	A	92	27	16	17	5
		B	632	97	44	28	5
	5.08 cm Pb	A	54	20	17	10	4
		B	533	102	45	15	4
Series II	No Pb	A	62	30	24	12	8
		B	509	101	35	15	9
	7.62 cm Pb	A	32	18	12	4	3
		B	412	92	46	15	6

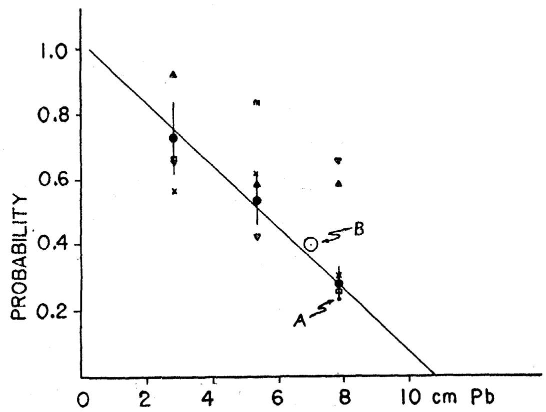

FIG. 7. The probability that a ray of a shower will penetrate a given thickness of lead. *A*, mean value uncorrected for efficiency; *B*, observations by first method. ϕ weighted mean values; Δ, 1.1 to 2.0×10^6 ion pairs; ∇, 2.0 to 3.0×10^6 ion pairs; $\times$, 3.0 to 5.0×10^6 ion pairs; $\square$, 5.0 to 10.0×10^6 ion pairs.

consideration, it is sufficient to employ the approximate expression:

$$P=E_0^2E_A(1-e^{-Np})^2(1-e^{-Npp'}). \qquad (1)$$

If we designate by P_A and P_0 the observed fraction of the bursts of ionization which were accompanied by a simultaneous discharge of the three counters with and without the absorber, respectively, we can solve Eq. (1) for p' thus:

$$p'=\log\,(1-P_A/E_AP_0^{\frac{2}{3}})/\log\,(1-P_0^{\frac{1}{3}}/E_0).$$

We notice that the value of p' so derived is independent of N and hence independent of the value of the specific ionization of a shower ray. The values of p' were calculated in this way for the first four groups of shower sizes in Table II, and are plotted in Fig. 7. The values of p' that we calculate are, of course, relative to the value of p' for the condition of no absorber, which value has been taken as unity. Now, even when no absorber is present, a ray of the shower, to discharge a counter, must pass out through the wall of the ionization chamber and through the wall and shield of the counter. The amount of material which it must traverse is 2.9 g/cm^2, which is equivalent to 2.5 mm of lead. Hence the abscissae in Fig. 7 have been displaced by this amount. The probable error for each value of p' was estimated in the usual way from the number of bursts observed and accordingly the weighted mean value of p' for each thickness of lead was computed. These mean values with their probable errors are also recorded in Fig. 7. The values of p' so obtained are largely independent of the efficiency of the counters. The point labeled *A* in Fig. 7 is the value computed assuming the efficiency of the counters to be 100 percent. It differs very little from the value computed when the actual efficiencies were taken into account, although the error introduced by assuming 100 percent efficiency would be greatest for this particular thickness of lead.

We see that, within the limits of the experimental error, p' decreases linearly with the thickness of the absorber and is independent of the size of the shower. The point labeled *B* in Fig. 7 represents the value of p' obtained by the ionization method described in the first section. The agreement between the two methods is thus very satisfactory. If we extrapolate the observations to obtain the maximum range of a shower in lead, we find a value of 11 cm.

Discussion

In the counter experiments on the absorption of showers, the number of counts observed[3] decreases very sharply with the introduction of a lead absorber a few millimeters thick, and then as the thickness of the absorber is increased, the number of counts decreases much more gradually. Of course, it is not possible to express the results of the counter observations directly in terms of the probability that a shower ray will penetrate the absorber, since the frequency distribution in size of the showers counted is not known, and hence the results of the present experiment may not be directly compared with the counter observations. Unfortunately the ionization chamber used for our experiments is so thick that the sharp initial decrease in the probability of penetration, if it were present, could not be observed. The measured probabilities of a shower ray penetrating a given thickness of lead, as given in Fig. 7, are relative values calculated by choosing as unity the probability when no additional absorber other than the chamber itself was present. However, the very gradual falling off of the number of showers, observed in counter experiments, as large thicknesses of lead are added is in good accord with the experiments here described.

These experiments emphasize again the fact that very large amounts of energy must be involved in the production of showers. Using Anderson's[10] value of the energy loss of electrons in lead, we see that at least half of the rays of the shower which emerge from the chamber have energies greater than 3×10^8 electron volts, and that the total energy in the showers which we observe must often exceed 3×10^{10} electron volts. It is also apparent that such penetrating powers as we observe are incompatible with the simple identification of the position of the maximum of a Rossi curve with the range of the shower particles.

An interesting consequence of these experiments is the quantitative agreement with the observations on the ionization produced in shielded and unshielded chambers in the stratosphere. As we go to higher and higher elevations, the contribution to the ionization of the extremely penetrating (primary) cosmic rays becomes smaller and smaller relative to the contribution of the secondary (shower) particles produced in the atmosphere. Thus we should expect that the percentage decrease in the ionization brought about by shielding the chamber should approach the value observed in the present experiments for the probability that a shower ray will be stopped in the shield. Bowen, Millikan, and Neher[11] have published a curve showing the variation with elevation of the decrease in ionization caused by a 6.5-cm lead shield, derived from their measurements and those of Compton and Stevenson.[12] The percentage decrease approaches the value of 68 percent as the elevation increases. The probability that a shower ray will be stopped in this shield thickness is 62 percent. Thus the observations are in accord with the interpretation suggested here.

The authors wish to express their gratitude to Professor W. F. G. Swann, in collaboration with whom a portion of these experiments were carried out, and whose interest and guidance throughout the course of this investigation have been invaluable.

[10] C. D. Anderson and S. H. Neddermeyer, Papers and Discussions, International Conference on Physics, London, 1934, I, p. 171.

[11] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **46**, 646 (1934).

[12] A. H. Compton and R. J. Stevenson, Phys. Rev. **45**, 441 (1934).

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Coincidence Counter Studies of Cosmic-Ray Showers

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It has been found that the production curves (counting rate against thickness of lead) of electron-produced and of photon-produced showers are similar and that the average penetrating power of the rays from electron-produced and from photon-produced showers is the same. Shower production curves have been obtained at four elevations and analysis of the curves shows that the absorption per nucleus of the shower-producing radiation (photons) is approximately proportional to the square of the atomic number. Coefficients for lead ($0.33\ cm^{-1}$), iron, and air have been determined, and a comparison with theory is given. Also the penetrating power of the shower rays emerging from a block of lead has been measured and found to be independent of the elevation and of the thickness of the lead from which the rays emerge.

1. Introduction

The cloud chamber photographs of Anderson *et al.*[1] and Blackett and Occhialini[2] have shown that cosmic-ray showers consist of groups of from two to several score electrons which are accompanied by numerous low energy photons. The shower-producing rays are usually non-ionizing, although the photographs of Stevenson and Street[3] show that ionizing rays may produce

[1] C. D. Anderson, R. A. Millikan, S. Neddermeyer and W. Pickering, Phys. Rev. **45**, 352 (1934).

[2] P. M. S. Blackett and G. P. S. Occhialini, Proc. Roy. Soc. **A139**, 699 (1933).

[3] E. C. Stevenson and J. C. Street, Phys. Rev. **48**, 464 (1935).