Showers Produced by Penetrating Rays and Allied Phenomena

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INTRODUCTION

THIS paper comprises two parts. The first concerns itself with an apparatus devised by Mr. W. E. Ramsey and myself for the purpose of recording shower phenomena produced by penetrating rays, and with the preliminary results obtained with that apparatus. The second part has to do with certain ideas as to the nature of cosmic-ray phenomena in the stratosphere initiated by the intensity zenith angle observations and the intensity altitude observations made by the Bartol Foundation during the first and second National Geographic U. S. Army Air Corps stratosphere flights and during the Jean Piccard flight.

PART ONE. AN APPARATUS FOR RECORDING SHOWERS PRODUCED BY PENETRATING RAYS

In its complete form and in its essentials, the apparatus comprises the following parts, Fig. 1:

First there are eight slabs of lead, shown cross-hatched, each 1 cm thick. Above each slab, as shown in B, C, D, E, F, G, H, I, is an array of Geiger-Müller counters. Each counter is 20 cm long and 1 cm in diameter. The counters are packed in trays, each tray forming a plane of counters with their axes parallel. Thus, a whole tray constitutes a square sensitive area, 400 square centimeters in size. Above this assembly is placed a slab of lead 18 cm thick, and on the top of this is placed an additional counter tray, A, similar to the others and still another tray, J, is placed below all of the slabs of lead, as shown in Fig. 1. Counting from the top downwards, the successive counter trays are arranged with their counters alternately in perpendicular directions.

Every counter is connected to an individual electroscope, so that in all there are 180 such electroscopes. Each electroscope carries a mirror, and by means of a suitably designed optical system each mirror is caused to shine a spot of light upon a ground glass screen, so that in principle we have ten parallel rows of spots, Fig. 2A, each row representative of the corresponding 18 counters in a single tray, as indicated by the lettering attached to the spots. In practice, it was found convenient to have two ground glass screens, each caring for five rows of spots in the manner sufficiently well symbolized by Fig. 2B.

Now, the electrical circuits associated with the counters are so arranged that none of these electroscopes are permitted to operate unless at least one counter in each tray discharges simultaneously.[1] The control thus provided insures that any electroscope deflection recorded is associated directly or indirectly with a ray which has passed through all nine slabs of lead, and which may thus be regarded, in general, as a penetrating ray. However, when the simultaneous discharge of one or more counters in each tray permits the apparatus to operate, the deflections of the electroscope spots which result provide a complete record of all that has happened as regards shower production in the various slabs of lead initiated by the passage of the penetrating ray which was responsible for operating the "master control."[2]

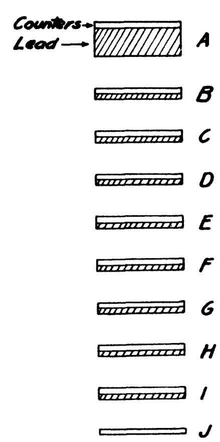

FIG. 1. Arrangement of counters and slabs of lead.

[1] As a matter of fact, it is not necessary to cause all of the ten counter trays to participate in this control feature. It is sufficient to invoke the trays A and J, together with as many others as are sufficient to insure the desired degree of resolution against strays.

[2] By the "master control" we mean the control provided by the feature that the electroscopes are only allowed to operate when at least one counter in each tray discharges.

The principle invoked in the "master control" may be described sufficiently clearly without reference to details of the circuit system associated with it. The principle is as follows: Each counter, for example, a, Fig. 3, is connected

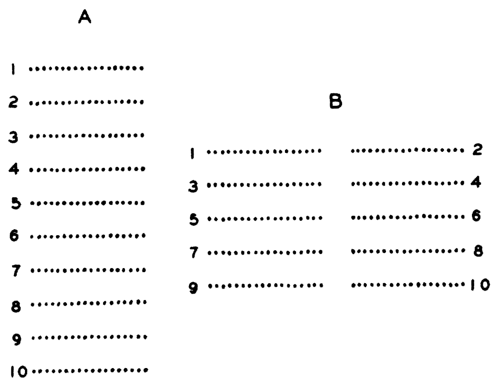

FIG. 2. Arrangement of spots on ground glass screen.

through a coupling capacity, c, to the filament, f, of the small rectifier whose other electrode, T, is connected to the moving element of an electroscope. The filament, f, is connected to the ground of the apparatus through the resistance, r_2, and the moving element of the electroscope is connected to the case surrounding all of the electroscopes through the high resistance, s. However, the electroscope case, and therefore with it the electroscopes themselves, is biased to the extent of 100 volts, by means of the battery E_1. Under these conditions, the moving element of the electroscope is unable to collect any charge which may result from the discharge of a counter. However, matters are so arranged that when the master control operates, the electroscope case receives a pulse which swings it about 100 volts in the positive direction. The moving element is thus swung by induction to a potential which is sufficiently positive in relation to its former value to insure that the filament will discharge to it, provided that the negative potential of that filament has been enhanced by the counter discharge. The electroscope is not deflected by the direct inductive action of the pulse itself, since that pulse is completed long before the inertia of the moving system has allowed it to move at all. The pulse simply permits the electric discharge to flow into the moving element, which then deflects at leisure, but of course, finally dies down to zero on account of the high resistance, s. The swing of the potential of the case is adjusted so that the moving element does not come by induction actually positive to the filament unless the negative potential of the filament is enhanced by the actual occurrence of a discharge in the counter associated with it. The magnitudes of the quantities shown in Fig. 3 are given in the caption.

Since the filaments of the rectifiers must be insulated, they are lighted by making an insulated coil associated with each secondary, J, of a transformer. Fig. 4 shows a complete tray assembly of counters with its associated transformer units and electroscopes. The secondaries of the transformers associated with the individual counters are aligned side by side with a common iron core which is excited by a single primary winding for each tray. The details of the unit will be sufficiently evident from the caption.

The eighteen electroscopes associated with each tray are made in groups of six, and one of these units of six is shown in Fig. 5. The electroscope is of the type involving a vertical moving leaf element swinging between two plates maintained at potentials equal and opposite in sign with respect to the normal potential of the case of the electroscopes as a whole. The moving elements of the electroscopes are supported by

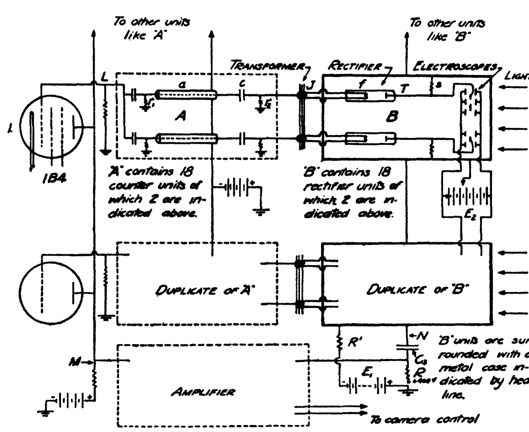

FIG. 3. Counters and electroscopes. The essential magnitudes are $r_1=4.5\times10^8$ ohms, $r_2=1.0\times10^6$ ohms, $s=10^{11}$ ohms, $R=2.0\times10^3$ ohms, $R'=1.0\times10^5$ ohms, $E_1=100$ volts, $E_2=450$ volts, $c=0.000025$ μf, $c_3=0.5$ μf.

very fine horizontal phosphor bronze wires, and, as already stated, each element is provided with a small mirror. Two adjustments are provided for each electroscope. One of these involves rotating the support of the phosphor bronze wire about a horizontal axis and this provides for rotation of the mirror parallel to a vertical plane. The other adjustment permits a rotation of the support of the whole moving element about a vertical axis and so provides rotation of the mirror parallel to a horizontal plane. The two plates which are maintained at positive and negative potentials with respect to the case are each made into single units which are common to all six electroscopes; and the parts of the plates immediately opposite the vertical moving element of each electroscope are cut away, so that the moving elements themselves may swing back and forth without hitting or sticking to the plates. The effect of cutting away these portions of the plates is such as to produce very little reduction upon the workable sensitivity of the electroscopes. Some circuit details are shown in Fig. 6, and their significance will be sufficiently evident from the caption.

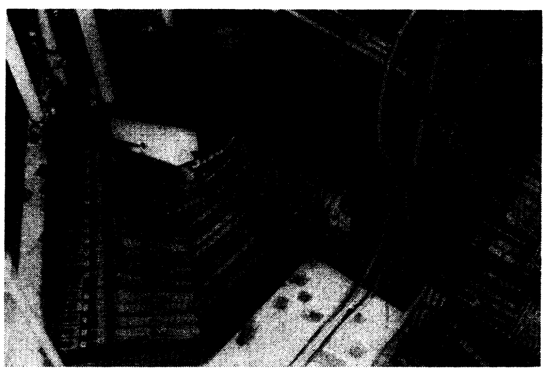

FIG. 4. The horseshoe-shaped elements to the left indicate the positions of the electroscopes, as will be understood by reference to Fig. 5. The transformer and rectifier elements are seen in the center of the picture, leading to a row of 18 counters shown by the cylindrical tubes immediately above the center.

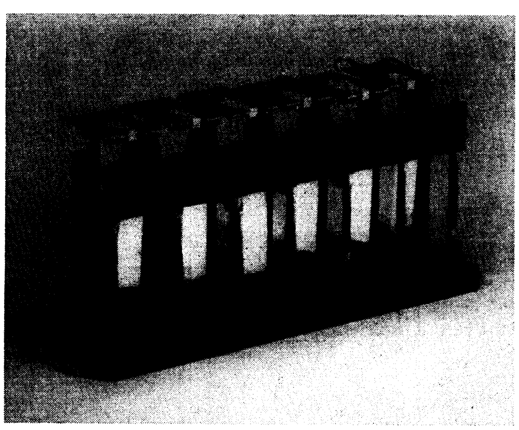

FIG. 5. Group of electroscopes.

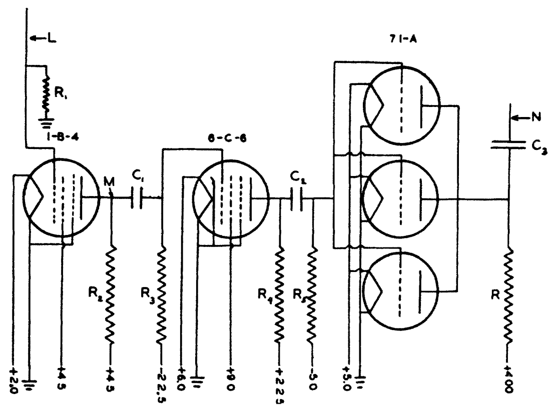

FIG. 6. The tube to the extreme left has its grid connected through the line L to a point which is common to one set of plates of a set of condensers—one for each counter of a tray—whose other plates are connected to the wires of the individual counters. The connection will be understood by regarding the wire L of Fig. 6 as identical with the wire L of Fig. 3, and regarding the tube to the left of Fig. 6 as being the representative of any one of the tubes to the left of Fig. 3. When these tubes are excited simultaneously by the discharge of at least one counter in each tray, they function, in a manner which will be sufficiently obvious, to operate the master control, in that they bring about a sudden change of potential between the ends of the resistance R, and so a sudden change of potential of the wire N which is connected to the case of all of the electroscopes. The essential magnitudes are as follows: $R=2\times10^3$ ohms, $R_1=1.0\times10^6$ ohms, $R_2=2.5\times10^4$ ohms, $R_3=5\times10^5$ megohms, $R_4=2.5\times10^4$ ohms, $R_5=1.0\times10^6$ ohms, $C_1=0.0002$ μf, $C_2=0.0006$ μf, $C_3=0.5$ μf.

Figure 7 shows an actual assembly of six counter trays. The optical system presented certain problems of interest; but it is hardly necessary to describe the system in detail.

Figure 8 is a picture of a tank containing 30 feet of water. The apparatus is installed in the lowest 12-foot section of this tank, below the water, this section providing a convenient room. The tank enables experiments to be performed for rays which have traveled through different thicknesses of water.

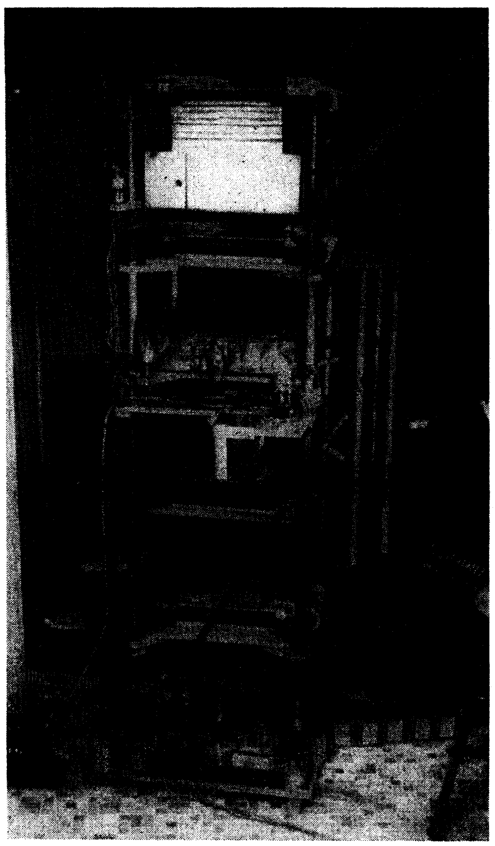

FIG. 7. Assembly of six counter trays.

A model to facilitate interpretation

The data from the experiments are obtained, as already stated, in the form of a number of rows of dots, one row to correspond to each counter tray and each row containing eighteen dots to correspond to the eighteen individual counters. A displacement of a dot from its normal position indicates a discharge of the corresponding counter. For the most ready interpretation of the data, however, it was found convenient to build a model of the counter trays, Fig. 9,[3] in which each tray was represented by a square unit of parallel wires with eighteen spaces between them to correspond to the eighteen counters, the lengths of the wires being parallel to the counters. Taking into account the fact that the counters in alternate trays are perpendicular to one another, it will be seen that four such alternate trays are sufficient, through their corresponding models, to determine completely the course of any ray which has passed through them and left its record in the form of the counters which it has discharged in the various trays. Thus, suppose we confine ourselves for the moment to the case of four trays and suppose that counter No. 3 in tray No. 1, No. 5 in tray No. 2, No. 2 in tray No. 3, and No. 7 in tray No. 4 have discharged. In this case a single ray has passed through the apparatus. We take a glass rod and pass it through space No. 3 in the upper tray of the model, then through space No. 5 in the second tray down, then through space No. 2 in the third tray. We find it still has one degree of freedom left, but on causing it to pass through space No. 7 of the last tray the direction of the rod becomes completely determined.

When more than one counter in each tray discharged, there is a certain ambiguity in the interpretation, because different rays can be drawn as representatives of the possibilities. However, some of these become eliminated as possibilities because it may be impossible to make a ray pass through the four counters—one in each tray—and yet fall within the limits of the apparatus. In other words, some of the rays which would have been possible for infinitely long counters become eliminated under the criterion of counters of finite length. In addition,

FIG. 8. Tank in which apparatus is installed. The upper part is filled with water. The apparatus is in the lowest 12-ft. section.

[3] The model is reduced by a factor of two, in relation to the actual apparatus, in the vertical direction.

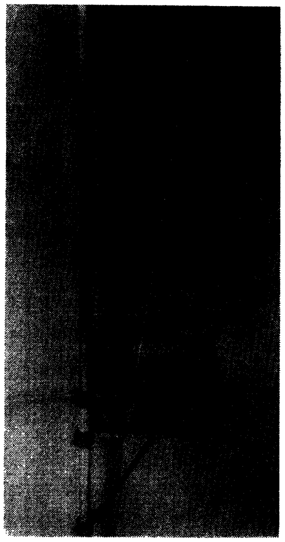

FIG. 9. Model showing passage of ray through the counters.

one finds that as one works with the model various other "principles of selection" evolve which serve to reduce the ambiguity even for as limited a number of trays as four, and this applies not merely to rays which traverse the whole apparatus, but to shower rays which have originated in the lead.

The data which follow were obtained from two sets of experiments, the first comprising 570 pictures taken in a 12-hour run, and the second, 555 pictures. The first experiment was performed with only four trays, and one slab of lead one centimeter thick in addition to the 18-cm slab at the top of the apparatus. The second experiment was performed with six trays, according to the scheme of Fig. 1, with corresponding 1-cm thick lead plates; but in addition there was an extra tray of counters whose plane was practically coincident with the lower face of the 18-cm slab of lead, and which was protected on all sides by a wall of 5 cm of lead. This extra tray was caused to function with the master control, but it was not provided with electroscopes. Its purpose was to prevent the apparatus from recording any large electron showers, coming in sideways, and which might otherwise simulate vertical showers by operating all the counter trays. In both sets of experiments the tank above the apparatus contained a 30-ft. column of water.

Discussion of data

Figures 10 and 12, taken in Experiment 1[4] represent on one slide a few representative pictures which will serve to illustrate the principles of analysis. Fig. 10A represents the simplest case and the one found in 84 percent of the pictures. It corresponds to a single ray which, reading downwards for the four trays, has passed through counters Nos. 5, 3, 9, 5. Its model is represented in Fig. 9. Fig. 10B shows a similar case obtained in Experiment 2, in which, in the successive trays (apart from the extra tray) counters 5, 16, 7, 16, 13, 16 discharged. Fig. 10C, from Experiment 1, shows, reading successively downwards, counters Nos. 4 in the first tray, 5 and 11 in the second, 2 and 12 in the third, and 9 and 11 in the fourth. We can symbolize this by the scheme (4) (5, 11) (2, 12) (9, 11).

An interesting case is represented in Fig. 10D (Experiment 1). It indicates a case of a primary

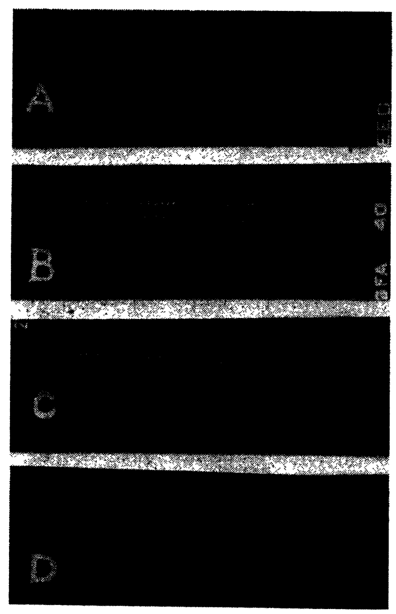

FIG. 10. Representative records.

[4] Since the spots do not remain constant in position, on account of temperature effects, etc., it is sometimes difficult to see what has happened from a single picture. However, certainty is achieved by comparison with the pictures immediately preceding or immediately following. Examination of the reproductions of Figs. 10, 12, and 13 in the proof reveals the fact that some of the elements in these pictures, which are quite distinct in the originals, will probably not be convincing to the reader.

ray producing a shower in a 1-cm thick slab of lead, with a resulting discharge of six counters in the third tray and seven in the fourth. The shower is presumably a six-ray shower (plus the primary), as indicated in the model, Fig. 11, one of the rays having failed to record in the third tray on account of inefficiency. There are, of course, several possibilities as regards the actual direction of this primary ray, since we do not know its true representative in trays Nos. 3 and 4. However, all of these possibilities are equivalent as regards the main interest of the story. With a larger number of trays, the possibilities would be more uniquely defined.

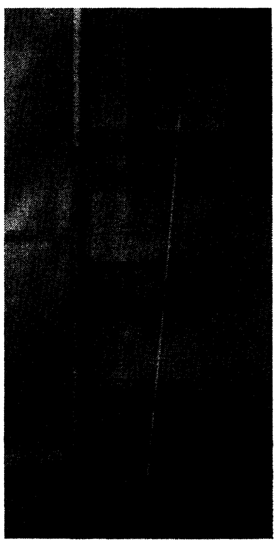

FIG. 11. Model of six-ray shower.

Figure 12A (Experiment 1) is an interesting but rather rare case. It can be represented symbolically by the scheme (14) (2) (10, 14, 16) (9, 13, 18). In spite of the discharge of three counters in each of the lower trays, the model shows that it is impossible to find four counters which have discharged, one in each tray, and draw through them a ray which will fall within the limits of the apparatus.

The most alluring interpretation of what has happened is that which invokes a primary ray *ending* in the 1-cm piece of lead and resulting in a three-ray shower which shows itself by the discharge of three counters in tray No. 3, and three in tray No. 4. If we wish to avoid the implication that the penetrating ray terminated its existence in the 1-cm slab of lead, we may do so by assuming that one counter in tray No. 3 and one in tray No. 4 was inoperative for it. This twofold inefficiency is unlikely. We cannot so readily escape the difficulty by supposing in actuality that there was only one inefficiency either in tray No. 3 or tray No. 4, and that the penetrating ray did in actuality pass through one of the counters in tray No. 3 or tray No. 4, for to do so would be to rob the three-ray shower of one of its counter records and so again invite a second inefficiency as part of the whole phenomenon. It is true that the counters, taking into account the spaces between, are only about 80 percent efficient, but a twofold inefficiency in the same composite act becomes reasonably unlikely. It is eonceivably possible to suppose that the primary ray escaped outside of the limits of the apparatus in the vicinity of the lower tray and escaped being recorded in this manner. The geometrical possibilities do not lend much support to this occurrence, so that we may in actuality be confronted with a shower resulting from the actual disappearance of a mesotron. Cases of this kind will become much less ambiguous when more counter trays are incorporated. Fig. 12B (Experiment 1) is represented by the scheme (2, 7) (9, 12) (6, 10)

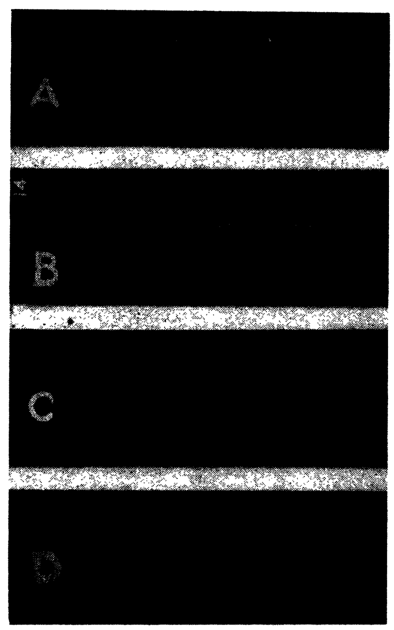

FIG. 12. Representative records.

(3, 10).[5] The obvious interpretation is that which invokes two hard rays passing simultaneously through the apparatus—however, one might think of the case as representative of a penetrating ray entering the upper tray in company with an electron ray, the latter becoming lost in the 18 cm of lead, but replaced by another electron ray generated as a shower ray by the penetrating ray in the 18-cm block of lead. The fact that just two counters discharged in each tray, combined with the rarity of the event of production of shower rays by the penetrating rays and by the further unusual circumstance which we should evoke in supposing an electron ray to traverse the 1 cm of lead without producing a shower, all of these considerations invite us to the belief that the simplest interpretation of the record is the most likely one, and this interpretation is to the effect that two penetrating rays entered the apparatus from above, probably as part of a shower composed partly of penetrating rays.

Figure 12C (Experiment 1), designated by the scheme (18) (5, 15) (2, 9, 13, 16, 17) (3, 5, 6, 9), represents a single entering ray which, on emerging from the 18 cm of lead, is accompanied by an additional ray which is presumably an electron. This electron produces multiplication to the extent of five rays in the 1 cm of lead, which five rays become reduced to four in the fourth tray, possibly by loss of rays through the boundaries of the apparatus, or by counter inefficiency.

Figure 12D (Experiment 1),[6] designated by (4) (12, 15, 18) (16) (2), is similar to the case last recorded, except that two additional rays emerge from the top piece of lead. These become absorbed by the 1-cm slab of lead, leaving only the single ray to pass through trays 3 and 4. It is also conceivable that these two rays may be lost by divergence from the apparatus between trays 2 and 3.

Figure 13A (Experiment 2) represented by (5) (4, 5, 8) (1, 3, 6, 11, 12, 13, 14) (1, 2, 11, 17, 18) (14, 15) (6, 9, 10, 11, 12, 13, 14, 18) represents a single entering ray which shows the phenomenon of growth and decay in the various slabs of lead.

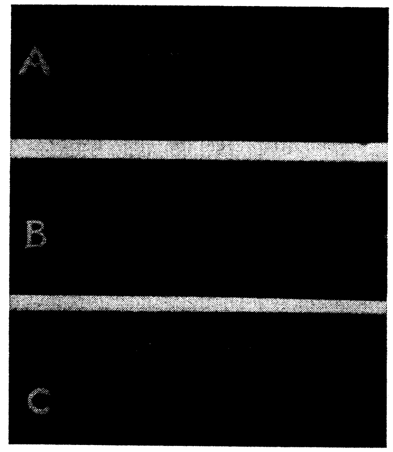

FIG. 13. Representative records

Figure 13B (Experiment 1) represents a situation in which a large proportion of the counters, including those above the 18-cm piece of lead, discharged. It possibly represents a portion of a large shower coming from above. In this case, it is natural to suppose that there are several mesotrons in the shower since, if there were only one, and if the remainder were electrons which were absorbed in the upper piece of lead, we should not expect a perpetuation of the abnormality represented by the discharge of so many counters into the trays below the upper piece of lead.

We cannot, of course, rule out absolutely the possibility of this kind of shower being one of exceptionally high energy electrons capable of penetrating 18 cm of lead. It is customary to suppose, however, that such an event is one of extreme rarity; and its rarity is enhanced in the present case by the 30-ft. column of water in the tank above the apparatus.

It is, of course, possible that the shower here shown originated from a very large electron shower which came in from the side so as to discharge at least one counter in each of the four trays. It is for this reason that the extra layer of nonrecording counters immediately below the 18-cm piece of lead, surrounded on all sides by 5 cm of lead, was employed in Experiment 2. In Experiment 2 one large shower of

[5] The spot corresponding to counter No. 8 happens to be off the film, but not as a result of counter discharge. That this is the case is shown by examination of preceding films.

[6] In the actual record, spots (8) and (9) are missing, not as a result of counter discharge. This is shown by comparison with preceding records.

this kind was recorded and is shown in Fig. 13C. It is characterized by the fact that in each of the six recording trays except the second, counting downwards, more than ten counters discharged. However, in the said second tray there were no counter discharges. The implication is that the shower here observed is an electron shower coming in at such an angle from the side that the tray which shows no counter discharges was shielded by the lead above it. However, even in such an explanation we are forced to admit that at least one penetrating ray existed in the shower, since one or more rays must have passed through the nonrecording tray immediately under the 18 cm of lead, and such rays must have passed through at least 5 cm of lead.

Correlation of the experiments with the theory of shower production

H. J. Bhabha[7] has developed a theory of shower production by mesotrons, according to which he calculates the number of cases in which, in the equilibrium condition in lead, a mesotron is accompanied by one electron, two electrons, or, in general, n electrons. E is the energy of the mesotron and m the rest mass. The numbers in question are given for a 100-electron mass mesotron, except for the case $E-mc^2=10^8$ where they are given for a 10-electron mass mesotron. They do not vary very drastically with the energy of the mesotrons over the range 10^8 to 10^{12} for the quantity $E-mc^2$. The theoretical data are, in fact, digested under "Theoretical" in Table I, the value for $n=3$ being interpolated from Bhabha's data. However, the numbers given represent the calculated number of cases in which, in 570 pictures (taken as our standard number of observations for comparison) we should expect a mesotron to be accompanied by one ray, two rays, $\cdots n$ rays. The numbers are for electrons of energy greater than 10^7 ev, the critical energy for lead. If energies below this are considered, the numbers should be doubled. Many of the electrons below 10^7 ev would, however, not record in our counters.

TABLE I. *Comparison of theory of shower production with experimental results. Number of cases out of 570 in which we would expect one mesotron of given energy specification to be accompanied by n rays.*

Energy Specification		$n=1$	2	3	4	5	6	7	8
		Theoretical							
	$E-mc^2=10^8$ ev	13.6	2.3	1.5	0.8	—	—	—	—
	10^{10}	26.0	8.0	5.6	3.2	2.1	0.7	—	—
	10^{12}	26.0	8.5	6.0	3.4	2.3	0.8	—	—
		Experimental							
Exp. 1	Below 18 cm Pb	11	5	1	2	1	1	1	1
	Below 19 cm Pb	13	4	3	0	3	0	0	0
Exp. 2	Below 18 cm Pb	7	3	0	0	0	1		
	Below 19 cm Pb	10	4	1	1	0	0		
	Below 20 cm Pb	12	2	1	0	0	0		
	Below 21 cm Pb	11	2	1	1	0	0		
	Below 22 cm Pb	9	1	0	1	0	0		
	Averages for all data	10	3	1	0.7	0.6	0.3		
	Corrected averages	12.5	5	2	1.7	1.8	1.2		

Below the theoretical values are contained our experimental results, obtained on observations below the 18-cm block of lead[8] and also on observations below the additional 1-cm pieces of lead. The individual numbers of rays in any one picture, below the 18 cm block are in general quite different to those below the additional slabs; but in view of the fact that equilibrium may be supposed to have been attained in 18 cm of lead, we should expect the averaged results for the two cases to be in harmony, as indeed they are within the limits of accuracy of the experiments, when one takes into account the large statistical fluctuations to be expected in the case of the smaller numbers.

The procedure adopted in obtaining these experimental results was to confine interest to those cases where (a) there was only one ray recorded in each tray, (b) a single ray through both upper trays with a multiplication for trays 3 or 4 or both, (c) cases where there were two counter discharges in the upper tray with multiplication below, and where the evidence was in favor of the assumption that the two entering rays were in actuality penetrating rays which passed right through the apparatus. There were only about five of these cases in all.

The average for all the cases is given in the next to the last row of Table I, and as regards order of magnitude it is, at any rate, in agreement with the theoretical values for energies within the range considered.

On account of the distances between adjacent counters, each tray was only 30 percent efficient.

[7] H. J. Bhabha, Proc. Roy. Soc. **164**, 257 (1938).

[8] While one cannot make observations in the lead itself, observations immediately below a thick block of lead obviously give the results desired.

This inefficiency means that approximately the data for $n=1$ should be raised by the factor 10/8, the data for $n=2$ should be raised $(10/8)^2$, and so on. The corrected averages are given in the last row of Table I. They are in very good *relative* agreement with the theoretical data for the range 10^{10} to 10^{12} for $E-mc^2$, but all differ from the theoretical data by a factor of about 2. Possibly a better agreement would be found in the ranges between 10^8 and 10^{10}. On the whole, however, the correspondence between the theoretical data and the experimental data is surprisingly good.

Occasionally the interpretation of a story could very satisfactorily be completed by invoking the assumption of inefficiency in one of the counters. Occasionally a pseudo-inefficiency could result in a manner not attributable to the counters, as when the counters discharged in the fourth tray, when combined in interpretation with those which discharged in the second tray, led to a point of origin in the lead such as to predict that of geometrical necessity two rays from the center of the shower must have passed through a single counter of the third tray. In all such cases half weight was given to the conclusion reached from such observations.

It may be a matter of general interest to remark that in connection with all the data obtained in foregoing experiments, including data not used in constructing Table I, data, for example, in which more than one counter discharged in the top tray, in all of this data about one out of every seven events recorded by our apparatus showed multiplicity of some kind.

In the 570 observations of the first experiment there was one case where the most obvious interpretation was that a mesotron had ended its course in the 1-cm slab of lead and there were two additional cases in which there was a possibility that this had occurred. The data from the second experiment have not yet been analyzed for this phenomenon.

There were six cases in which more than three counters in the upper tray and more than three in each of the other trays discharged in the data for the first experiment. In the data for the second experiment there were no cases in which more than three counters discharged in all of the trays, so that the implication is that in the first experiment this phenomenon was caused by electron showers coming in from the side.

In the first experiment there were four cases in which at least eight counters discharged in the upper tray with a copious discharge of counters in the lower trays. In the second experiment there were two such cases.

There was, in the first experiment, one case where 17 counters discharged in the first tray, 15 in the second, 13 in the third, and 13 in the fourth.

Evidence for mesotrons in showers

When there is perpetuation of two or more simultaneous rays through one or more blocks of lead of thickness 1 cm, the evidence is in favor of the assumption that the rays are mesotrons, as a chance of an electron ray passing through such a slab of lead without resulting multiplication is small. The certainty of a phenomenon being representative of mesotrons is increased, of course, as the number of slabs of lead through which the rays pass without multiplication is increased. For these reasons, it is felt that the following citations give, at any rate, preliminary evidence of the occurrence of mesotrons in showers:

In the 570 pictures of Experiment 1, there were three cases where a single ray entering the 18-cm block emerged as two rays which passed through an additional 1-cm block without multiplication. In the 555 pictures of Experiment 2, there were two cases where a single ray entering the 18-cm block emerged as two rays which passed without multiplication or reduction through four individual 1-cm blocks of lead.

Taking the case where two rays entered the 18-cm block and emerged as two rays, there were three cases in Experiment 1 where these rays continued as a pair through an additional centimeter of lead, and in Experiment 2 there were two cases where the rays continued without multiplication or reduction through the four single slabs of lead.

In Experiment 1 there were three cases in which a single ray entering the 18-cm block emerged as more than two rays, which passed through the additional 1-cm block without multiplication or reduction.

In Experiment 2 there was one case of a single

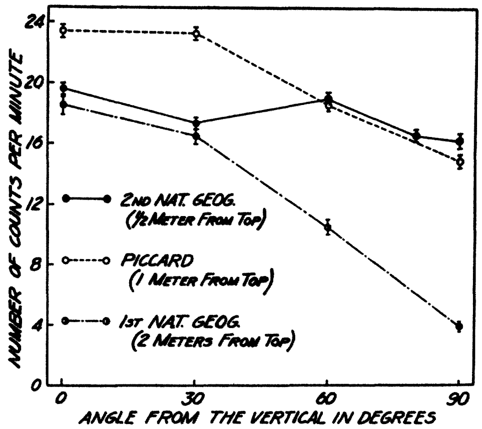

FIG. 14. Intensity *vs.* zenith angle from flights in the stratosphere.

ray entering the 18-cm block emerging as four and passing through the additional four individual 1-cm blocks without multiplication or reduction.

In conclusion I should like to express my thanks, not only to Mr. W. E. Ramsey, who has participated throughout in the development of this apparatus and in the observations, but also to Mr. D. B. Cowie, who has rendered invaluable assistance in connection with the observations and analysis.

PART TWO. CERTAIN CONSIDERATIONS PERTAINING TO COSMIC-RAY PHENOMENA IN THE STRATOSPHERE

In the National Geographic U. S. Army Air Corps stratosphere flights made by *Explorer I* and *Explorer II*, and in the Jean Piccard flight, the Bartol Foundation made observations of the variation of cosmic-ray intensity with altitude for various zenith angles. It was found that at the higher altitudes the diminution of intensity with increase of zenith angle from the vertical was much less rapid than would be expected if the intensity in any direction were determined simply by the line integral of the atmospheric density from the point of observation upwards to infinity along the direction concerned.[9] The intensity *versus* zenith angle data for these flights are, in fact, given in Fig. 14.

It was found that in the flight of *Explorer I*, at an atmospheric depth the equivalent of 2 meters of water, the horizontal intensity formed 25 percent of the vertical. In the Piccard flight at a water equivalent depth of 1 meter the horizontal intensity was 50 percent of the vertical, and in the flight of *Explorer II* at a water equivalent depth of 0.5 meter the horizontal intensity was 80 percent of the vertical.

At first sight one might think that at a water equivalent depth of half a meter the line integral of the density to infinity in a direction tangential to the horizontal at the point of observation might be so small as to account for the large horizontal intensity. That such is not the case is borne out by the following considerations. Suppose we consider a direction defined by a zenith angle[10] θ given by $\cos\theta = 0.1$, the point of observation being at a water equivalent depth of 0.5 meter. On the basis of the assumption of an absorption depending upon the line integral of the density, we should expect for a direction given by $\cos\theta = 0.1$ an intensity equal to the vertical intensity at a depth of ten times 0.5 meter of water. Our vertical intensity curves show that the vertical intensity at 5 meters depth is only 17 percent of that of 0.5 meter depth. However, the intensity as measured for the direction given by $\cos\theta = 0.1$ differs from the measured vertical intensity at the same altitude (0.5 meter of water) by less than 20 percent. Hence, our zenith angle results cannot be accounted for on the basis of an absorption depending only upon the line integral of the density.

One may have a suspicion that there is some uncertainty in our observations resulting from the finite angular spread of our telescopes. However, this uncertainty is much less than might at first sight be supposed. The counter areas were square areas 3 cm in side, and the distance between the extremes of a telescope unit was 9 cm. However, it is easy to show that, even in the most unfavorable case, that in which there is no component of radiation upwards, one of our telescopes, when pointed horizontally, should measure the intensity at an angle from the

[9] The assumption that the intensity is determined entirely by the aforesaid line integral is usually stated by asserting that the intensity is a function only of $h \sec\theta$, where θ is the zenith angle.

[10] The choice of a zenith angle not quite 90^0 avoids the irrelevant complications introduced by the curvature of the earth.

horizontal which is of the order of only one-third of the extreme angular limits of the telescope. In other words, it should measure the intensity at an angle of about one-ninth of a radian or about eight degrees from the horizontal.

The earth's magnetic field has some influence in altering the intensity-zenith angle relation from what it would be in the absence of the field. As primary cosmic-ray particles enter the atmosphere, they produce showers by the ordinary multiplicative process, and in the absence of a magnetic field the strong perpetuation of direction by the progeny results in directional measurements which, of course, involve, for the most part, the progeny, giving direct evidence of the variation of intensity with direction for the primaries. When a magnetic field is present, however, the situation is altered. While the path of a primary of energy sufficiently great to enter the earth's atmosphere through the earth's magnetic field would be bent but little in a few kilometers, for example, the progeny of that ray, in virtue of their low energy, would experience much greater bending, so that without further investigation we cannot conclude that the actual directional measurements made, involving as they do the effects of the progeny, can be true representatives of the directional effects of the primaries.

However, while the effect of the earth's magnetic field upon the secondaries is of great interest in discussions of the relation of directional measurements within the atmosphere to those which would be obtained if one could operate outside of the limits of the atmosphere, we cannot invoke the magnetic field as the sole agency responsible for the large intensity observable in directions approximating to the horizontal, and for the following reasons:

The kind of bending to which I have referred and resulting from the earth's magnetic field will tend to enhance the horizontal intensity only in planes approximating to a plane perpendicular to the magnetic lines of force. Therefore, on this basis alone, we should expect no enhancement of horizontal intensity in the magnetic meridian at the magnetic equator. Thus in general, if the phenomena concerned were attributable to the magnetic field, we should expect a variation of horizontal intensity with azimuth. Now, our data obtained in the flight of *Explorer II* gave, at the maximum altitude, a remarkable symmetry with azimuth. The intensity from the east differed from that from the west by less than 1 percent, and both intensities differed from the average for all azimuths by less than 1 percent. It is true that in latitudes comparable with 50°, which was representative of the latitude of the flight of *Explorer II*, the lines of force are more nearly vertical than horizontal, so that the interpretation of the phenomenon is more complicated and, indeed, the magnetic field has less effect of the kind under discussion than in equatorial regions. However, Dr. Johnson's recent measurements at low latitudes give no evidence of a pronounced variation of intensity at large zenith angles with azimuth. For these reasons, I think we must look for some effect other than the magnetic bending for an explanation of the large intensity at large zenith angles. This does not mean that the magnetic effect is not present. It simply means that there must be some other effect which tends to give uniformity of intensity in all directions in the stratosphere, and with this effect operating, the magnetic field cannot, of course, alter the homogeneity appreciably.

We can account for the uniformity of intensity in all directions in the stratosphere if we assume that there is a component of the incoming radiation which becomes absorbed in the higher regions of the atmosphere and produces, possibly after a certain time delay, secondary bursts of radiation which are symmetrical in all directions.

Theoretical considerations prevent its being a matter of great ease to realize a condition in which secondary bursts of rays occur in such fashion that the rays travel out from a center more or less symmetrically in all directions. In the case where the particles concerned have velocities comparable with that of light, the laws of conservation of energy and momentum conspire to insure in the secondary particles a strong perpetuation of the direction of the primary particles. However, if we invoke an intermediate stage in which particles of velocity considerably less than that of light are formed, but with a rest mass sufficient to provide, on disintegration, for lighter particles with velocities comparable with that of light, we can provide an explanation of the phenomenon. Thus, to consider a specific possibility, suppose that a primary particle should enter our atmosphere and give rise to mesotrons on collision with the atoms of the air. If some of these mesotrons have velocities appreciably different from that of light, it is permissible for them to travel in directions quite different from that of the primary particle, or even to be born at rest. We are, in fact, not interested in the actual velocity of these particles or of their directions. Regarding some of these particles as approximately at rest, we realize that with a mean life of only 10^{-6} of a second, they could not travel more than 300 meters on the average without disintegrating, even if they traveled with the velocity of light, and indeed we are assuming that they travel with a smaller velocity than that of light. When a mesotron disintegrates, it shoots out an electron and a neutrino. Since we are assuming the mesotrons to be at rest, the electrons will come out on the average in random directions, so that the intensity, insofar as it results from this contribution, should tend to equality in all directions in the stratosphere and, indeed, there should be an appreciable intensity in upward directions from below. I may say that following this suggestion Dr. S. A. Korff has designed and is actually carrying out an experiment to test for such upward intensity.

As we descend from the higher regions of the stratosphere, we may expect to find the homogeneity of the radiation in all directions become diminished because the mesotrons which reach to these levels are those which have lived long enough to do so. In other words, since mesotron life increases with kinetic energy, these mesotrons must be those of velocity comparable with that of light. In the system of axes moving with one of these mesotrons, the disintegration of the mesotron may occur with equal probability in any direction, but when we transfer this story to fixed axes we find a favoring of the forward direction for the electron emission, which fact represents simply another aspect of the conservation of energy and momentum considerations already referred to. Thus, as we descend through the stratosphere into the lower regions of the atmosphere, we may expect the symmetry of emission to diminish, until finally we approximate to the intensity-zenith angle curves found at low altitudes. In other words, the conclusions are in harmony with our experimental findings.

We have avoided as far as possible any definite suggestion of a mechanism to provide for the mesotrons referred to above in such a manner as to realize the conditions which we have envisaged. However, one naturally tends to think of the phenomenon as happening through radiative processes associated with losses of energy of the primary, these radiative processes giving rise to photons of different energies. From these photons, by processes analogous to pair production for electrons, one may suppose mesotrons to be created, the variety of kinetic energies ranging from zero upwards.[11]

Presumably, one cannot rule out absolutely an explanation of large intensities at great zenith angles founded upon the large scattering associated with the lowest energy electrons originating in the cascade process. Intensity zenith angle measurements with suitable thicknesses of lead between the counters should serve to test this matter conclusively. If, as seems likely, the scattering phenomenon is insufficient, it would seem that we are driven to accept some such process as that envisaged above and depending upon something like a mesotron intermediary. If we do accept this process, however, we are faced with a strange situation as regards the ordinarily accepted origin of the soft component through the supposition of entering primary electrons with subsequent initiation of the cascade process. For the cascade process provides primarily for perpetuation of direction of the primaries, apart from magnetic field considerations, and there is thus no room for it as an agency superposed upon a theory which provides for symmetry in all directions if we seek to account for a resulting situation in which there is practically a quality of intensity for all zenith angles from zero to 90°. It is, of course, possible to imagine that the process additional to that resulting from the primary electrons itself gives a lack of symmetry which, when combined with the unidirectional symmetry

[11] It may be remarked that if we trace the consequences of an entirely different type of assumption founded upon the idea that the mesotrons which are created move on the average symmetrically in the system of axes in which the primary particle is at rest, then on the basis of such ideas it is possible to develop certain interesting consequences, particularly in connection with large showers. These matters will be reserved for a future communication.

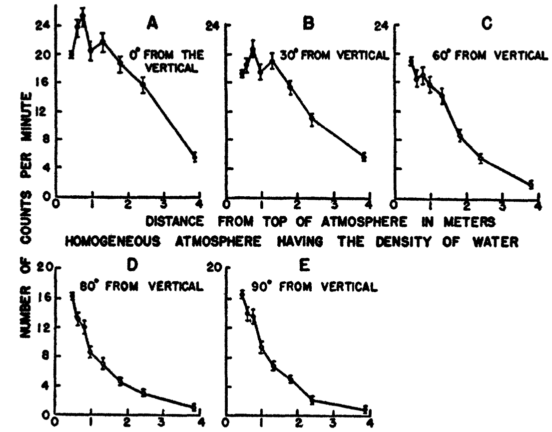

FIG. 15. Data from flight of *Explorer II.*

of the ordinarily assumed process, results in the symmetry observed. Such a compensation, however, appears unlikely.

If, therefore, the process postulated to account for symmetry leaves no room for primary electrons, the said process must itself look after the story of the soft component. We may then have to revert to some such picture as that which I presented as part of a symposium held at the University of Chicago last year[12] in which, from a primary background of nonelectron origin, there resulted—not necessarily in single acts—the creation of high energy electrons which perpetuated themselves through pair formation in such manner that, governed in part by the properties of the primary component, they were able to tell the story of both the soft and the hard components of cosmic radiation as ordinarily understood.

The elementary cascade process gives rise to a single maximum in the intensity altitude curves. If the cascade process is supplemented by an additional process such as that connected with the mesotron formation of the kind cited above, we may expect two maxima in the intensity altitude curves. In this connection, it is of interest to observe the data shown in Fig. 15, obtained from our experiments in the flight of *Explorer II.* Referring to *A*, for example, it will be seen that there are two maxima. If one had only this single curve to rely upon, he might have doubts as to the reality of these maxima. However, the maxima are shown in diminishing degree in each of the curves *B, C, D, E,* for successively increasing zenith angles; and while all of these data were obtained at the same time, it is to be observed that each of these curves represents the results from an entirely different counter telescope.

[12] W. F. G. Swann, J. Frank. Inst. **226**, 757 (1938).

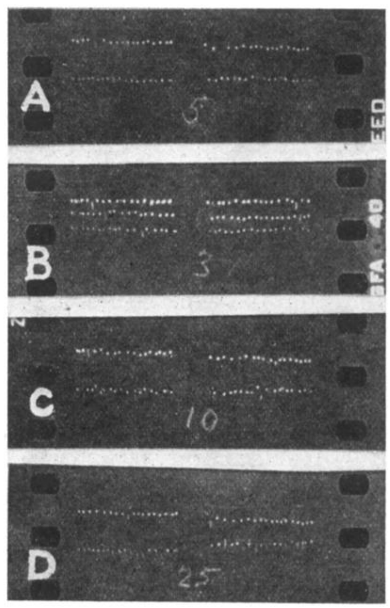

FIG. 10. Representative records.

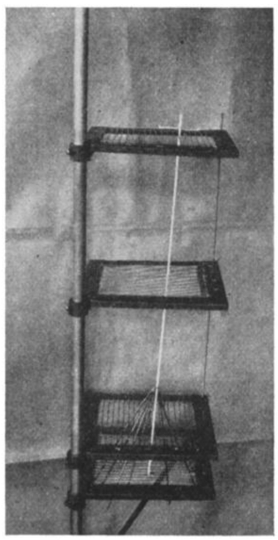

Fig. 11. Model of six-ray shower.

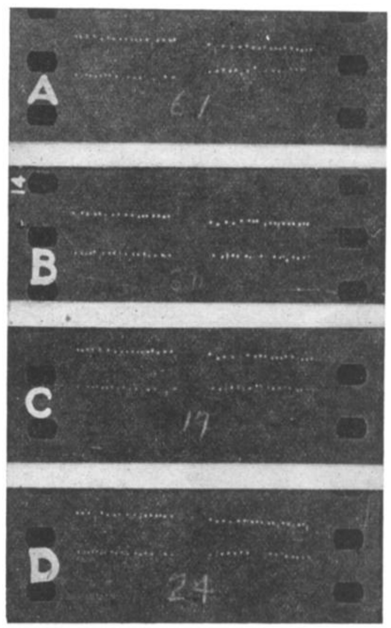

FIG. 12. Representative records.

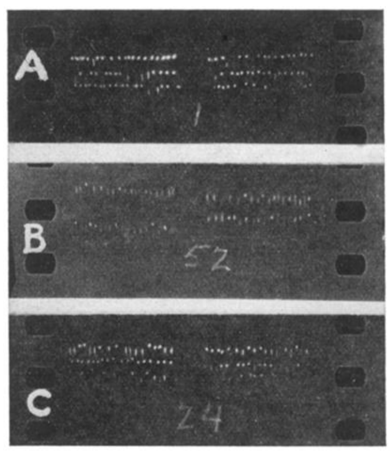

Fig. 13. Representative records.

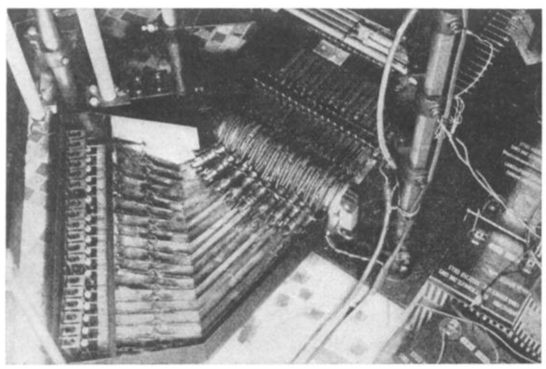

FIG. 4. The horseshoe-shaped elements to the left indicate the positions of the electroscopes, as will be understood by reference to Fig. 5. The transformer and rectifier elements are seen in the center of the picture, leading to a row of 18 counters shown by the cylindrical tubes immediately above the center.

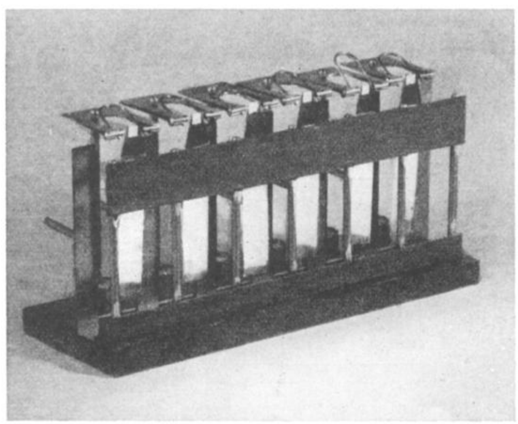

FIG. 5. Group of electroscopes.

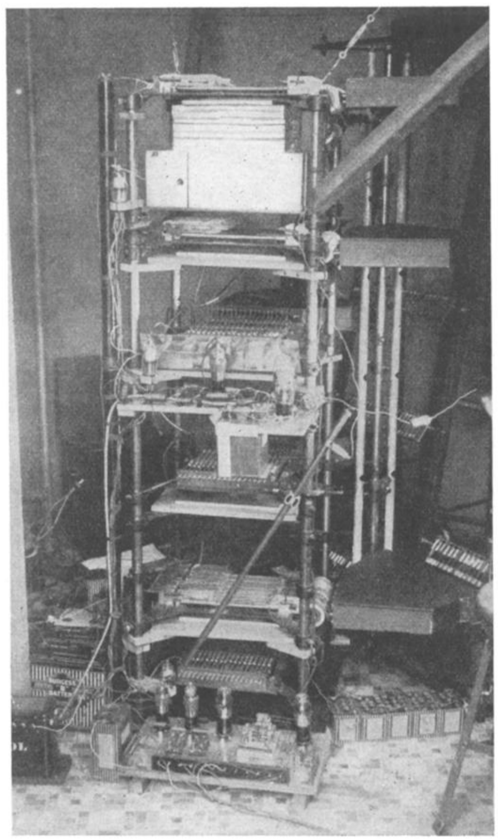

FIG. 7. Assembly of six counter trays.

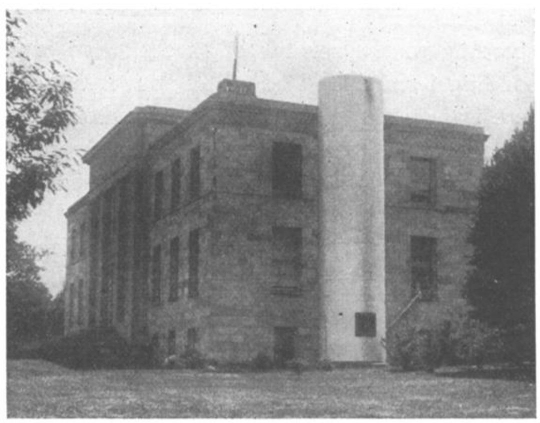

FIG. 8. Tank in which apparatus is installed. The upper part is filled with water. The apparatus is in the lowest 12-ft. section.

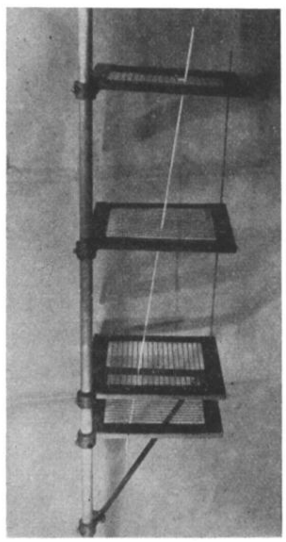

FIG. 9. Model showing passage of ray through the counters.