THE SOURCE OF THE PENETRATING RADIATION FOUND IN THE EARTH'S ATMOSPHERE

by

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A THESIS

Submitted to the Faculty of

California Institute of Technology

in Fulfillment of one of the

Requirements for the Degree of

DOCTOR OF PHILOSOPHY

1924

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INTRODUCTION

Since the time of Coulomb, investigators have noticed a loss of charge from bodies insulated in air in closed vessels which has seemed too large to be accounted for by leak across the insulating support. Matteucci (Annales de Chim. et de Phys., v.28, p.385, 1850), as early as 1850, found that the loss of charge was independent of the potential and that the leakage decreased on lowering the pressure of air in the closed vessel. Warburg (Annalen der Physik u. Chemie, v.145, p.578, 1872) also found that the leakage decreased with a decrease in pressure. This, of course, indicated that some property of the air or one of its impurities was responsible for part of the observed loss of charge. The validity of this conclusion was further attested by some experiments of Boys who measured the loss of charge, using quartz insulators of different lengths and diameters. The generally accepted explanation of these experiments up to about 1900 was that the leakage took place through convection of the charge by dust particles present in the enclosed air.

The subject was a dead one until the discovery was made that gases could be ionized and were therefore made conducting by the action of Roentgen rays and rays from radium; attention was then drawn anew to the problem. Elster and Geitel (Phys. Zeit., v2, p.116, 1900) and C. T. R. Wilson (Proc. Camb. Phil. Soc., v.11, p.32) announced in 1900 that dust-free air enclosed in air-tight chambers is conducting when no known ionizing agent is present, and that the rate of loss of charge is independent of the potential and is the same for positive and negative charges. They both found the same results at night as in the daytime. Wilson also found the rate of leak proportional to the pressure. Since these experiments demonstrated that the loss of charge from an insulated body was not due to the presence of dust particles and was not the effect of any known ionizing agent present, the hypothesis of "spontaneous ionization of air" was taken as the explanation of the phenomenon. Later, however, C. T. R. Wilson (Proc. Roy. Soc., v.69, p.277, 1902) found that the "spontaneous ionization of air" was present when other gases were used instead of air, and that the ionization in the various gases was roughly proportional to their densities except in the case of hydrogen. Since Strutt (Phil. Trans., A, v.196, p.507) found the same relative ionizations for the same gases when subjected to the rays from radium, Wilson thought that the observed ionization might not be spontaneous at all, but might be the effect of Becquerel rays from the walls of the electroscope. Evidence for the truth of this suggestion was found in the experiments of J. Paterson (Proc. Camb. Phil. Soc., v.12) in which it was noted that when large vessels were used, the ionization was not proportional to the pressure, but, instead, tended toward a maximum as the pressure was increased. This indicated an alpha radiation from the walls of the vessel, for, if the vessel is large, as the pressure is increased the alpha rays will soon be all absorbed within the vessel and then any further increase in the pressure will not change the ionization produced by these rays. Conclusive evidence that part of the ionization was caused by rays from the walls of the electroscope was got by Strutt (Nature, v.67, p.369, 1902). He found that when he used for his ionization chamber cylinders of the same dimensions but of different materials, he got different values of the ionization. Up to this time, then, the explanation for the loss of charge from an insulated body in an air-tight vessel was that the air was made conducting through ionization by alpha rays from the walls of the vessel. These alpha rays might come from a trace of radium in the wall metal or they might come from the metal itself. Campbell concludes from his experiments that part of the rays are characteristic of the metal itself.

The discovery that the rays come not only from the walls of the vessel but also from external sources was announced simultaneously by Rutherford and Cooke (Phys. Rev., v.16, p.183, 1903) and McLennan and Burton (Phys. Rev., v.16, p.184, 1903). Rutherford and Cooke, taking account of the fact that the active deposit formed on a negatively charged wire in the open atmosphere is similar to that formed in the presence of radium and thorium, were led to look for a radiation from the atmosphere. They surrounded their electroscope with 2 mm. of lead and found no difference in the ionization. When they surrounded it with 5 cm. of lead, however, the rate of discharge was cut down by 30%. There was no greater change on adding five tons of pig-lead. They also found that the ionization was cut down 30% by 5 cm. of iron and by 70 cm. of water. On removing the screens, the ionization always returned to its original value. McLennan and Burton, in their experiments, found that a screen of 25 cm. of water cut down the rate of discharge 37%. While there is not very good quantitative agreement between the two experiments, they both show conclusively that part of the radiation observed in an electroscope comes from outside the apparatus itself. Rutherford and Cooke thought that it came from an active deposit on the walls of the laboratory in which they made their experiments until they found the same thing occurring over frozen ground outside the laboratory. The result of all this is that there is a penetrating radiation present in the earth's atmosphere, coming apparently from all directions, and the problem then became one of locating the source of this radiation.

It became evident at once that the intensity of this external penetrating radiation depends a great deal on location and meteorological conditions. Gockel (Jahr. d. Rad. u. Elek., v.9, p.4, 1912) finds these values of the ions per cm.^{3} per sec.

produced in his electroscope: in a garden, 9.5; in a hole in the garden, 12.0; on a balcony, 13.5; in a room, 12.0; in a tunnel of granite, 33.5; in an ice chamber, 3.1 . From this, it is obvious that a considerable portion of the radiation comes from radioactive bodies in the immediate neighborhood. That some of this comes from the ground is evidenced by the decrease in the radiation over bodies of water which is found by all observers. The quantitative results will be given more in detail in a later chapter, so suffice it to say here that the contribution from the ground which is assumed to be cut off by the intervening water when over bodies of water is about 3 ions per cm^3 per sec. That some comes also from the atmosphere or from some extraterrestrial source is shown by the decrease in radiation from values on water surfaces which is in general observed when the electroscope is lowered into the water. The detailed results of this work will be given later. The agreement between different observers is not very good; but this is to be explained by the different radium contents of the bodies of water chosen and by actual differences in the radium emanation content of the atmosphere in the several places.

Perhaps the most spectacular discovery in connection with the problem was that with an increase in altitude above the ground the radiation does not decrease in intensity as one might expect it to. Instead, after a certain height is reached, the radiation becomes stronger. If all the radiation came from the ground, Eve (Phil. Mag., v.21, p.26, 1911) has calculated that the radiation should fall to half its intensity at about 80 m.above ground. Actually, Wulf (Phys. Zeit., v.11, p.811, 1910) found 3.5 ions per cm^3 per sec. due to the penetrating radiation on the Eiffel Tower (300 m.), while there were only 6.0 ions per cm^3 per sec. at the foot of the tower. Bergwitz (Habilitationsschrift, Braunschweig, 1910) and McLennan and Macullum (Phil. Mag., v.22, p.639, 1911) find values more in agreement with Eve's calculation. Bergwitz finds a decrease of 50% when he goes into a church tower 85 m. high, while McLennan and Macullum get a decrease of 25% on a tower 64 m. high. Gockel (Phys. Zeit., v.11, p.280, 1910), however, in a balloon at 4000 - 4500 m. finds the radiation not much less than at the ground, and in a later experiment (Phys. Zeit., v.12, p.595, 1911) concludes that there is a slight increase in radiation with increase in altitude. Hess (Phys. Zeit., v.12, p.998, 1911) finds first a decrease up to 440 m., then a slight increase. Later, Hess (Phys. Zeit., v.13, p.1084, 1912) made a balloon flight as high as 5200 m. and found a very large increase in ionization with altitude. The experiments of Kolhörster (Phys. Zeit., v.14, p.1153, 1913 and Deutshe Phys. Gesel., July 30, 1914) show the same effect. Kolhörster has made several balloon flights to very high altitudes, the last one being to 9000 m. At that altitude, the ionization was 80.4 ions per cm^3 per sec. more than at the earth's surface. The detailed results will be tabulated in another place where they can be most easily compared with the results of the author.

This observed increase in intensity of the penetrating radiation with altitude is a most startling and extraordinary effect, because it means that as one goes away from the earth he is getting closer and closer to some radioactive source. It throws serious doubt on the notion that most of the radiation comes from the ground and the immediate surroundings on the earth. Indeed, it leads one to suspect that the sun or some of the other heavenly bodies may be sending out gamma rays of the necessarily high penetrating power, or that a layer of cosmical dust hovering on the outskirts of the earth's atmosphere may be the source of the radiation. But this explanation is hampered by difficulties, chief of which is that such a radiation would have to come through a thickness of atmosphere equivalent to 76 cm. of mercury, and, in order to do that, the radiating bodies would have to be radioactive to a perhaps unreasonable degree. Furthermore, on this view, the absorption coefficient would have to be far smaller than that of the most penetrating gamma radiation known. Another possible explanation is that there is radioactive matter distributed throughout the atmosphere in such a way as to produce the observed radiation. The difficulty here is to explain why there is more of this radioactive matter at high altitudes than at the surface of the earth. It is evident that whatever explanation is finally accepted, a radically new and important fact will be born.

The investigations of the author were undertaken with the purpose of aiding in finding the correct explanation of the existence and behaviour of this troublesome so-called "penetrating radiation." They may be divided, perhaps, into three parts: first, finding out whether or not the "penetrating radiation" really increases in intensity as one goes to higher altitudes; second, demonstrating the falsity of some of the most obvious of the possible explanations; third, measuring the absorption coefficient of the radiation at a high altitude in order to compare it with the absorption coefficients compatible with the various theories.

I. APPARATUS AND METHOD OF OBSERVATION

1. DESCRIPTION

Throughout all the investigations, the electroscope used to measure the ionization due to the penetrating radiation was the one pictured in Figs. 1 and 2 and diagramatically shown in Fig. 3. This electroscope, which is of the Wulf type, was designed and constructed in the shops of the Norman Bridge Laboratory of Physics. Two quartz fibres of about 0.005 mm. to 0.01 mm. diameter and about 6 cm. long, sputtered with platinum to make them conducting, are at the top soldered together into a small copper tube which is held by a set-screw in a brass cap, A, which is cemented to a long rod of quartz insulation. At their lower ends the fibres are fastened by a bead of shellac to a bow of unsputtered quartz fibre of slightly greater diameter. This insulating bow provides the resisting tension to the charged fibres and brings them together when the charge decreases. The ends of the bow are attached to brass pieces, B, whose effective lengths are adjustable, so that the fibres can be brought to the most efficient tension. This tension is one that will allow full-scale deflection when the electroscope is charged to the desired potential, but is still sufficient to make stable the fibres and to bring them together when uncharged. The screws for adjusting the tension on the fibres pass through an invar bridge which is supported by invar rods, C, which are in turn hung from approximately the same point in the top that supports the quartz insulator. Thus, the tension is not changed by any deflection of the electroscope case due to a difference in pressure between the inside and the outside. Furthermore, inasmuch as the invar used was tested and found to have a temperature coefficient of expansion practically equal to that of quartz, the tension of the fibres should be independent of temperature also. This was found to be the case.

The case of the electroscope was made from cylindrical brass tubing, 1.7 mm. to 1.8 mm. thick. The bottom was of brass, 3 mm. thick, while the top was of rolled zinc and most of the metal parts connected with the top were turned from zinc castings. An entire case of zinc was first tried, but it was found almost impossible to make the zinc casting air-tight under high pressures. The case used, however, was air-tight under a pressure of 60 lbs. per square inch above atmospheric pressure. The enclosed air was kept dry by phosphorus pentoxide which filled the flat cylindrical box, D, at the bottom of the electroscope. This box, which is covered by a perforated top to keep the phosphorus pentoxide from being shaken out where it might cause trouble, screws onto a lug projecting from the bottom of the case.

The positions of the fibres were determined with the aid of a microscope having a scale in the eyepiece. A window on the opposite side of the case provided light. Sunlight was used when possible; in other cases, a small flash-light bulb attached to a projection over the window was employed. The position of the objective as well as the eyepiece of the microscope could be varied, for the whole microscope fits into a tube which extends into the case of the electroscope and terminates in a small glass window. This arrangement is very convenient because it is possible by simply removing the microscope to lower the electroscope into deep water without any protection and without fear of a leak. The fibres are kept in the focal plane of the microscope by the strengthened field due to the bent aluminum wires, E, projecting from the supporting invar rods. A very thick soft rubber gasket separates the top of the electroscope from the sides, so the fibres could easily be swung into the center of the field of view by tightening the proper screws in the top.

The outside electrical connection to the fibres is made through the charging rod, F, which in the "on" position touches the brass cap to which the fibres are attached, and in the "off" position touches the case. This charging rod, as it passes through the case, is tapered at a very small angle to fit a greased ebonite bearing and is held tightly into contact by a strong spring.

A feature of the electroscope is that it was possible to entirely eliminate insulation loss if the loss across the thin quartz bow was neglected, and this is valid because of the negligibly small diameter of the bow compared with the upper insulator.

The quartz insulator is held in a brass rod which passes through an ebonite plug to the outside of the electroscope. It was, thus, possible to maintain the brass rod at the mean potential of the fibres throughout a period of observation and thereby make impossible any insulation loss to the case. The brass rod and the quartz insulator are shielded from the rest of the electroscope by the shield, G, which is made in two parts, one of which may be rotated with respect to the other, leaving an opening to facilitate cleaning the insulator.

2. CONSTANTS OF THE ELECTROSCOPE

The fact that the electroscope was designed most efficiently to accomodate lead screens accounts for the absence of projections from it and also for its not being larger. Of course, had it not been desirable to screen it with lead, it would have been better for it to have been larger, but economy dictated the volume. The volume of air in the electroscope was 1893. cm^3.

The sensitivity varied in the different experiments from 1.4 to 2.1 volts per scale division.

The capacity of the insulated system was found to be 1.32 cm. It was determined as follows. In Fig. 4, C' is a standard condenser; C is the electroscope with the fibres connected to the outside through the charging switch and a small projecting wire fastened to the charging switch; A and B are stiff wires attached to the ends of an electrically driven tuning fork of vibration frequency equal to 50; D is a Wilson tilted-leaf electroscope. As the fork vibrates, contact with A charges the fibres and contact with B discharges them. It is obvious that in this process the condenser C' loses some of its charge, and that the rate of loss of charge depends on the capacity of the fibres. To determine this capacity, then, it remains only to note the change in potential of C' in a given time. Actually the procedure is to charge the condenser C', set the fork vibrating and measure with a stop-watch the time required for the leaf of the tilted-leaf electroscope to pass over a given number of scale divisions. This electroscope is then calibrated in volts. If q is the instantaneous charge and e the instantaneous potential difference of the condenser C', and q' and e' are the charge and potential difference after one vibration of the fork,

$$q' = q - \Delta q$$

but $$\Delta q = eC \quad \text{and} \quad q = eC'$$

therefore $$q' = eC' - eC = e'C'$$

or $$e' = \frac{e(C' - C)}{C'} = e\left(1 - \frac{C}{C'}\right)$$

$$\Delta e = e - e' = e\,\frac{C}{C'}$$

This is the change in the potential difference across the condenser C' due to one vibration of the fork. Now if $\frac{C}{C'}$ is very small, we can write

$$de = (\Delta e)n\,dt$$

$$= e\frac{C}{C'}n\,dt$$

or

$$\frac{de}{e} = \frac{C}{C'}n\,dt$$

Integrating,

$$\log_e \frac{E}{E'} = \frac{C}{C'}nT$$

where E and E' are the potential differences across the condenser C' before and after the interval of time T. Hence

$$C = \frac{C'}{nT}\log_e \frac{E}{E'}$$

It is necessary in using this method that the capacity of all connecting wires be negligible compared with C'. The fact that the values found for C using successively two standard condensers of capacities 0.2 mf. and 0.5 mf. agreed to within 1% was taken to mean that this condition was fulfilled. It is also necessary, in applying the formula mentioned above, that the insulation loss and the natural leak of the Wilson tilted-leaf electroscope during the interval of time T be wholly negligible. This was found to be the case.

The capacity thus determined is the capacity of the fibres and the charging rod and the wire projection which makes contact with A and B. The capacity of the fibres alone is found from this by the following method. The charging rod, carrying the wire projection in the same position as in the previous determination, is brought into contact with the fibres. The system is then charged to a very high potential which is measured with a voltmeter, and the charging rod is drawn away from the fibres, and, after the potential has been removed, is grounded to the case. In this condition, if Q_f is the charge on the fibres, C_f the capacity of the fibres and P the potential of the fibres,

$$Q_f = C_f P$$

The charging rod is then brought again into contact with the fibres and Q_f is shared by the rod and the attached wire. This causes the fibres to come to a lower potential, P', and we have

$$Q_f = CP'$$

Therefore $$C_f = \frac{CP'}{P}$$

This potential P' may be got by noting the position of the fibres after the charging rod has been brought into contact with them and then calibrating the fibres against the voltmeter.

3. METHOD OF OBSERVATION

Of course, essentially what is done in making a measurement of the penetrating radiation is to charge the electroscope to a known potential and note the change in potential of the insulated fibres in a given interval of time. Then from this data and the known capacity of the fibres together with the volume, V, of enclosed air in the electroscope and the charge, e, on an electron, the rate of production of ions per unit volume can be calculated. Thus, the number of ions per cm.^{3} per sec which are formed is

$$\frac{C_f \Delta P}{3600\ Ve}$$

where P is the drop in potential of the fibres per hour.

The author found, however, that simply the difference in the positions of the fibres as read on the scale was not an accurate measure of the potential drop of the fibres, especially after transportation of the electroscope from one place to another. Therefore, inasmuch as the electroscope was necessarily subjected to rather severe treatment, in order to destroy all doubt as to the meanings of the readings, the electroscope was calibrated before and after every period of observation. This was easily and accurately accomplished by charging the electroscope to four known potentials in the region where lay the reading to be interpreted. The four points thus obtained were plotted and a straight line was drawn through them. The four points almost always lay quite close to the line, and never was it possible to make any large error. Calibration at the time of reading is considered very necessary to accurate results, for it was found that, while the sensitivity might not change appreciably, the whole calibration curve might from time to time move to the side, thereby changing the meaning in volts of a given deflection of the fibres. This possibility of error was completely eliminated by the method employed in these investigations.

The diagram of connections is shown in Fig. 5. When the switch S is in position 1, the battery is connected to the charging rod and to the case; when it is in position 2, it is connected to the guard ring on the quartz insulation and to the case. The 40000 ohms resistance, R, is inserted in the electroscope circuit to avoid destructive currents if the charging rod should accidentally be brought into contact with the case while the switch S is still in position 1. Because no current flows through the electroscope, this resistance does not interfere with the measurement of potential.

The procedure to make an observation, then, is as follows. The charging rod is in the neutral position. The switch S is closed to position 1. The voltmeter switch is closed , a suitable potential is found on the battery, and the charging rod is connected to the fibres. The deflection of the fibres and the voltage are then read as nearly simultaneously as possible. The charging rod is removed to neutral and a potential about 4 volts lower is found. The fibres are again charged and the deflection and voltage are read. This is repeated until four comparisons between deflection and voltage have been obtained. The fibres are then charged to a potential lying in the midst of the four potentials previously applied, the charging rod is brought to neutral, the switch S is lifted to the neutral position and the charging rod is turned so that it touches the case. The deflection and the time are then observed. This deflection is afterward interpreted in term of volts and gives the potential at the beginning of the period of observation. The potential is now adjusted to equal the mean value of the potential of the fibres to be expected during the period of observation, the voltmeter switch is opened, and the switch S is closed to position 2, thereby putting this potential on the guard ring at the top of the quartz insulator and making impossible insulation loss. This potential need not be adjusted accurately, because the insulation loss is probably negligibly small anyway. The guard ring was used only to make unnecessary criticism of the results on the basis of insulation loss. At the end of the period of observation, the switch S is lifted to the neutral position, and the deflection of the fibres and the time are noted. The charging rod is turned to neutral and the process of calibration described above is gone through in order that the deflection just observed may be interpreted in volts.

There are several precautions which must be taken. First, saturation potential must be had at all times. Saturation potential is the potential on the insulated system which is required to remove all the ions produced before they have had an opportunity to recombine. It is obvious that if a potential lower than this were used, the rate of discharge of the insulated fibres would not be a true measure of the radiation passing through the electroscope. From tests, it was concluded that potentials over 100 volts were well above the saturation potential, so the electroscope was never operated at a potential lower than this.

Another precaution that must be observed is to allow plenty of time after closing the electroscope for the radium emanation, which was introduced into the electroscope with the air, to die out before observations on the penetrating radiation are made. The activity of the emanation decreases to half in 3.85 days. In these experiments, no observations were made sooner than two weeks after the electroscope had been closed and in most cases more than a month intervened. Furthermore, in those cases in which the electroscope was used after having stood two weeks, the enclosed air had been passed through coconut charcoal to remove any emanation present. This source of error, therefore, does not enter.

The product of disintegration of radium emanation bears a positive charge, and is consequently drawn onto negatively charged bodies, forming on them a deposit which is strongly radioactive. For this reason the case of the electroscope was connected to the positive side of the battery rather than to the negative, and all negatively charged wires leading from the battery were shielded by metal tubing.

II. ALTITUDE MEASUREMENTS OF PENETRATING RADIATION IN AIRPLANES AND BALLOONS

1. IN BALLOONS AT LOW ALTITUDES

In May, 1922, some observations were made at comparatively low altitudes in captive balloons at Ross Field, Calif. (elevation 150 m.) The results obtained are listed in Table I.

Table I.

ALTITUDE M. ABOVE GROUND	IONS PER CM.^{3} PER SEC. ABOVE GROUND VALUE	
	May 11	May 15
152		-1.2
305	-1.1	
457		-1.6
610	-3.3	
762		-2.4
1067		-1.2

It is observed that, with the possible exception of the observation at 1067 m., the values on each day are consistent within themselves but that they do not fit in perfectly with those taken on the other day. This is to be expected, and only means that there are in the locality varying conditions such as changing winds which make a difference in the radioactive content of the atmosphere.

The results are in general agreement with those of other observers. That is, they all find a decrease in intensity of the penetrating radiation with increase in altitude up to a certain point, at which it begins to increase. The value found at 1067 m.

seems too high; and perhaps this may be considered as evidence for the reality of an effect reported by Gockel (Phys. Zeit., v.11, p. 280, 1910) in which he finds that in the presence of clouds the penetrating radiation is stronger. He explains this on the basis of the discovery of Mme. Curie that active deposit serves as condensation nuclei for water drops. The observation at 1067 m. was made on the very top edge of a dense cloud almost 600 m. thick which covered an area of about 8 km. radius; so if the effect is real it certainly should have shown here.

In these measurements in balloons, the ionization was taken over periods of one hour.

2. IN AIRPLANES AT HIGH ALTITUDES

Measurements of the penetrating radiation were also made at altitudes up to 5340 m. in airplanes. The observed increases in ions per cm.^{3} per sec. over ground values are to be found in TableII.

Table II.

ALTITUDE, METERS ABOVE SEA LEVEL	IONS PER CM.^{3} PER SEC. ABOVE GROUND VALUE	
	Flight 1	Flight 2
760	-4.0	
1370	-3.6	
1525		-2.8
1985	-0.9	
2440		+0.2
2585	-4.4	
3355		+3.4
3505	+1.5	
4115	+1.8	
4270		+8.6
5185	+8.8	
5340		+5.1

Flight 1 was made in May, 1922 at March Field, Calif. (elevation 455 m.) Here, the discharge was measured over periods of from one-half to three-quarters of an hour.

Flight 2 was made in March, 1923 at Rockwell Field, Calif. (sea level) The plane used in this flight is shown in Fig. 6. In this series of observations, the discharge was measured over periods of one-half hour.

In these airplane flights the electroscope was suspended in front of the observer's seat by three pieces of ordinary laboratory rubber tubing, attached at their upper ends to the sides of the cockpit or to the gun-mount. The instrument was kept from swinging by another piece of tubing fastened at one end to a plug which screwed into the bottom of the electroscope and at the other end to the floor of the cockpit. The electroscope was thus made stable and free from the effect of vibration of the airplane motor.

The method followed was to go to the highest altitude attainable in a reasonable time, maintain the airplane accurately at that altitude during the period over which ionization was to be measured, then drop down to the next altitude, etc. Because of the limit to the amount of gasoline that can be carried to those high altitudes and the long time required to reach them, it was never possible to make observations at more than three different altitudes on the same day. Flight 1 and Flight 2, then, are not really single flights but series of flights made on consecutive days, and this may account for some of the irregularities in the data. For example, the observation at 5340 m. in Flight 2 was the only one made on that day, and is the only one which does not fit well in this series. The day this observation was made, it was very windy and dense clouds lay at an altitude of about 1500 m. over an area 50 km. or more in radius. The other observations in this series were taken in clear weather. Of course, some irregularity may be accounted for by error, for it was probably possible, under the extreme conditions of observation, to make an error of as much as 1.5 ions per cm^3. per sec.

In Table III. are given the results of measurements in free balloons made by Hess and by Kolhörster. From these, it is to be seen that Kolhörster also got different values on different flights, and that Hess found different values using two similar electroscopes which were read simultaneously. Further, it is evident that the increase in intensity of the penetrating radiation found by these observers is considerably more than that found by the author. The work of the author, however, is in agreement with that of Millikan and Bowen (Phys. Rev., v.22, p.198, 1923) in which pilot balloons carrying recording electroscopes were sent to altitudes of over 15 km. They found an increase in intensity of the penetrating radiation only one-quarter of that predicted from an exprapolation of Kolhörster's data. This work was done at Kelly Field, Texas.

Table III.

A means altitude in meters.
I means ions per cm^3 per sec. above ground value.

HESS (Phys. Zeit., v.13, p.1084, 1912)

A	I Instrument 1	 Instrument 2
0 - 200	-0.9	-0.7
200 - 500	-0.8	-1.4
500 - 1000	-0.7	-1.5
1000 - 2000	-0.4	+0.3
2000 -3000	+1.0	+1.5
3000 - 4000	+3.5	+4.7
4000 - 5200	+18.1	+15.4

KOLHÖRSTER (Phys. Zeit., v.14, p.1153, 1913)

Flight 1		Flight 2		Flight 3		Flight 4	
A	I	A	I	A	I	A	I
310	-1.2	500	-2.0	1090	-1.2	1000	-1.5
760	-1.3	600	-1.4	2130	+2.1	2000	+1.2
1650	+0.8	1000	-2.1	3550	+7.0	3000	+4.3
2110	+1.3	1400	-1.7	4700	+14.5	4000	+9.3
2400	+3.1	1500	-0.8	5600	+27.5	5000	+17.2
2600	+4.3	2400	+3.1	6200	+29.3	6000	+28.7
3000	+7.5	3300	+4.5			7000	+44.2
3400	+8.9	4000	+6.7			8000	+61.3
3500	+11.1					9000	+80.4

Assuming that Hess and Kolhorster had no insulation loss at those high altitudes, and that they got correct values without calibrating their electroscopes when under the existing abnormal conditions as was done by the author, there are several possible explanations of the different rates of increase in intensity of penetrating radiation found by those observers on the one hand, and by Millikan and Bowen and by the author on the other. First, the penetrating radiation may actually be more intense at high altitudes in Germany than it is at high altitudes in the south-western part of the United States. Second, the values obtained at high altitudes may depend on the means by which the high altitudes are reached; that is, values found in free balloons might differ from those found in airplanes or in pilot balloons even if the measurements were made in the same place at the same time. This would be expected if a large part of the observed radiation came from an active deposit on the balloon or airplane. This explanation is thrown by Hess (Phys. Zeit., v.12, p.998, 1911) because he found normal values of the ionization near the balloon case immediately after landing, and it is eliminated by Gockel (Phys. Zeit., v.11, p.280, 1910) who found nearly the same ionization at 4000 - 4500 m. as on the ground when the balloon could not have been charged because of having passed through dense clouds from which fine snow was falling.

Despite the quantitative differences, qualitatively all agree. It can be said that as one goes to higher and higher altitudes, the intensity of penetrating radiation first decreases to a minimum after which it increases continuously as high as observations have been made. The rate of increase, however, is not agreed upon.

III. INDEPENDENCE OF RATE OF DISCHARGE AND TEMPERATURE

This puzzling increase in penetrating radiation with altitude was explained by Kunsman (Phys. Rev., v.16, p.349, 1920) as being due to measuring an increased insulation loss and not an increased radiation. The increased insulation loss, he said, was a consequence of the lower temperature experienced at the high altitudes, and he published an account of experiments in which this effect of temperature was observed. His apparatus was equipped with two ionization volumes, in such a way that when one or both volumes were used, the ionization was recorded by the action of the same insulated system. Hence, by employing first one volume and then both volumes, he was able to calculate the insulation loss which was the same in both cases. At temperatures below -15 degrees Centigrade, he found that the leak across the insulation continually increased with decreasing temperature. By comparing the values of ionization found by Kolhörster at high altitudes and the values resulting from interpreting as ionization the insulation leak found at corresponding temperatures, Kunsman showed that the increase in ionization observed by Kolhörster could be explained as an insulation leak, provided that Kolhörster's electroscope behaved similarly to his own in this respect.

While a leak across the insulation was considered to have been eliminated in the electroscope used by the author, it was thought well to see if the effect found by Kunsman could be obtained with this electroscope when no attempt was made to counteract insulation loss. At normal room temperature, the ionization was 10.7 ions per cm^3. per sec. When the electroscope was partially surrounded with solid carbon dioxide, so that the temperature at the middle was about -50 degrees Centigrade, and at the top, -15 degrees Centigrade, the ionization was 10.5 ions per cm^3. per sec. When the instrument was almost completely surrounded, so that the temperature at the middle was about - 70 degrees Centigrade, and at the top, -30 degrees Centigrade, the ionization was 9.4 ions per cm^3. per sec. That is, instead of a huge increase in the rate of discharge, a slight decrease was observed. The decrease may be explained as due to either the reduction of the penetrating radiation by absorption in the solid carbon dioxide or to the natural variation of the penetrating radiation; in any case, there is no increase in the rate of discharge with decreasing temperature in the apparatus used. Therefore, in view of the results obtained by the author at high altitudes, this effect cannot be urged as an explanation of the increase in penetrating radiation with altitude.

IV. OBSERVATIONS ON MT. WHITNEY

1. CONTINUOUS OBSERVATIONS AT 4130 METERS

On Sept. 16,17,18,19, 1922, twenty consecutive observations, each lasting two hours, were made at Bench Mark No. 15 of the United States Geological Survey on the trail to Mt. Whitney, at an altitude of 4130 m. The apparatus in this location is shown in Fig. 7. The results of the experiment are recorded in Table IV.

Table IV.

MEAN TIME OF OBSERVATION	IONS PER $CM.^3$ PER SEC.
8:50 P.M.	19.2
10:58 "	18.9
1:05 A.M.	19.2
3:12 "	18.9
5:19 "	19.2
7:26 "	20.0
9:31 "	20.7
11:37 "	19.4
1:43 P.M.	18.6
3:50 "	19.8
5:59 "	19.2
8:03 "	19.6
10:07 "	19.3
12:12 A.M.	19.4
2:18 "	19.8
4:26 "	20.0
6:33 "	20.4
8:40 "	19.9
10:49 "	20.0
12:54 P.M.	21.0
	MEAN = 19.6

It is evident that at high altitudes there is no great difference between the penetrating radiation at night and in the daytime. Indeed, most of the variations from the mean are so small as to almost be accounted for by observational error, although the chance of error in these observations is less than in those made in airplanes. That there is no great difference between the day and night radiations is born out by tests (to be described later) made on Pike's Peak by Prof. R. A. Millikan and the author, and by Kolhörster who, however, finds a small diurnal variation of amplitude about the same as the variations in the values in Table IV.

It is clear, then, that the radiation which we measure does not come directly from the sun, for if it did, the night and day radiations would certainly be different. If it is a gamma radiation with which we are dealing, and if its source were the sun, in order to be consistent with the observations in Table IV., this radiation at night would have to come undiminished in intensity through the whole thickness of the earth, which is absurd. It may still be a secondary radiation ; but it cannot be a direct radiation from the sun.

2. OBSERVATIONS AT 3660 METERS

Observations were also made at U.S.G.S. B.M. 14, a point lower down on the trail, at an elevation of 3660 m. At this point there was a lake about 1 m. deep, 60 m. wide and 110 m. long. Two sides of the lake looked out to an open valley and distant mountains.

On one of the other sides, at a distance of about 2.5 km. rose the series of tall peaks of which Mt. Whitney is the highest. On the other side lay a progression of terraces which started at a distance of about 60 m. and reached a height of 30 m, at a distance of 100 m.

At this lake, two short logs were roped together to form a raft. The electroscope was then fastened to this raft and floated out onto the lake. In Fig. 8, it is shown in position on the lake. At the end of the period over which discharge was measured, the electroscope was pulled ashore and read. Observations were also made on land. In both cases the period over which discharge was measured was two hours.

On the lake, the radiation coming from the ground should be reduced to a very small quantity, for if this radiation proceeds from any known radioactive material it should be completely cut out by the 1 m. of intervening water. Therefore, the difference between the value found on the land near the lake and the value found on the lake should be an indication of the amount of radiation from the ground below. Any radiation from the rising ground at the sides of the lake will not affect this conclusion because the same radiation would be present in both cases. This radiation must be quite small, however, on account of the small solid angle subtended by those rocks which are close enough to have any effect.

On the land near the lake, the mean of two observations gave 17.3 ions per cm^3 per sec. On the lake, the mean of two observations gave 13.6 ions per cm^3 per sec. This means that the radiation from the ground is 17.3 - 13.6 = 3.7 ions per cm^3 per sec.

The first thing to notice is that the difference between the mean values at 4130 m. and at 3660 m. is of the same order as that found in airplanes. Not only the difference between them, however, but the absolute values agree very well if from them is subtracted the mean value in the open at Pasadena and the amount of radiation coming from the ground. That this must be done in order to make a just comparison may be seen from the following. If, for example, 3.7 be subtracted from the value found at 4130 m., the result is the radiation which would exist at that altitude if the ground were not present. This, then, would correspond to the radiation which would be observed in an airplane at that altitude. Hence if the ionization observed in Pasadena (elevation 240 m.) be subtracted from the result found above, the difference should correspond to that obtained in airplanes between the values of ionization at 4130 m. and on the ground. The mean of observations on the campus of California Institute of Technology is 9.33 ions per cm^3 per sec. Making the calculations explained above, one gets at 4130 m. an increase over ground value equal to 6.6 ions per cm^3 per sec., and at 3660 m. an increase of 4.3 ions per cm^3 per sec. It will be seen that these values agree well with those of Flight 2 in Table II.

The fact that the radiation was only reduced 3.7 ions per cm^3. per sec. when that part of the radiation proceeding from the ground was cut off means that the increased radiation observed on Mt. Whitney cannot be explained by a greater radioactivity of the soil. This reduction is a perfectly normal one, for on a float over a lake in Westlake Park, Los Angeles, Calif., a mean radiation of 6.37 ions per cm^3. per sec. was found, being a reduction of 3.0 from the value in Pasadena. In this experiment, the float was about 75 m. from the land, and the water was 2.5 m. deep. Some results of other observers are as follows:

McLennan (Phys. Rev., v.26, p.526, 1908)

Lead electroscope on land	11.2 to 13.2
" " over ice on lake	8.6 to 9.2
Zinc electroscope on land	11.1
" " over ice on lake	6.0
Aluminum electroscope on land	10.4
" " over ice on lake	6.55

McLennan (Phys. Zeit., v.13, p.1177, 1912)

On land	7.3 to 9.1
Over Lake Ontario	4.5
Over the ocean	5.4 to 6.6

McLennan and McLeod (Phil. Mag., v.26, p.740, 1913)

On University lawn	8.1
On Lake Ontario	4.93
On the ocean	4.33

Kunsman (Phys. Rev., v.16, p.349, 1920)

Basement of laboratory at Univ. of Calif.	8.68
Pacific Ocean between San Francisco and Los Angeles	4.15

Wulf (Le Radium, June,1910; Phys. Zeit., Sept., 1910)

Found reduction of 4.9 over a lake.

It is seen that these results agree very well with those of the author.

The conclusions to be drawn from the work on Mt. Whitney are:

1. The ground on Mt. Whitney is very little, if any, more radioactive than the ground in the vicinity of Pasadena.

2. The penetrating radiation on Mt. Whitney is more intense than at Pasadena by an amount which, when the effect of the ground is considered, agrees well with observations in airplanes.

3. This additional radiation comes from the atmosphere or from some source outside the atmosphere.

4. This additional radiation is not a primary gamma radiation from the sun.

V. ABSORPTION EXPERIMENTS ON PIKE'S PEAK

1. DESCRIPTION

In order to learn something about the quality of the large penetrating radiation observed at high altitudes, Prof. R. A. Millikan and the author, in Sept., 1923, made some experiments on Pike's Peak, Colorado (elevation 4300 m.) in which masses of lead up to 300 lbs. were used to shield the electroscope.

In order to support this mass of lead, it was necessary to use a steel frame which consisted of two vertical rods that supported two ring-shaped plates. On the bottom plate rested the electroscope and the sides of the shield, while the top plate held the top of the shield. The bottom of the shield was placed on a steel strip and brought up to the bottom of the electroscope by adjustable screws.

The shield was constructed of lead sheets a little less than 7 mm. thick. The cylindrical sides were made in two parts, so that either or both of the sides of the electroscope could be shielded. The top and bottom shields were just circular plates of the same sheet lead. These were all numbered, and were always placed on the electroscope in the same order with the same faces toward the electroscope. This was done in order to eliminate any inconsistency which might result from one plate being more radioactive than another.

The construction was very flexible, for any or all of the sides of the electroscope could be shielded with any number of lead sheets up to seven, or any side could be left unshielded. In Fig.9, the electroscope is shown completely shielded out-of-doors on Pike's Peak. In Fig. 10, it is shown indoors on the Peak with the sides shielded by seven layers of lead sheets, the top shielded by sixteen layers, and the bottom open.

The building and the room in which the in-door observations were made requires some description because it is of some importance in interpreting the observed results. The walls of the building are of rock, 60 cm. thick. The roof is of wood with a thin metal covering. The floor is probably from 30 to 60 cm. above the ground. The walls of the room in which the measurements were made were from 2.5 to 2.9 m. in height. The electroscope was placed 1.7 m. from the west wall, 3.7 m. from the north wall, 2.7 m. from the south wall, and 15. m. from the east wall. This building is shown in Fig. 11.

2. RESULTS

The means of the observations out-of-doors in the location shown in Fig. 9 are presented in Table V. The measurements in-doors are given in Table VI. It will be noticed that this data is divided into two parts: BEFORE THE STORM and AFTER THE STORM. This storm referred to was a rather bad wind and snow storm in which 20 or more centimeters of snow fell.

Table V.

A	Unshielded	23.2 ions per cm^3 per sec.
B	Shielded (4.8 cm. of Pb.)	11.6
C	Top only unshielded	12.3
D	Bottom only unshielded	13.2
E	North side only unshielded	16.9
F	South side only unshielded	16.7
G	Both sides unshielded	20.55

On the tower(17 m. high) of the building, the mean of two observations was 17.3

Table VI.

	UNSHIELDED	SHIELDED	TOP UNSHIELDED	BOTTOM UNSHIELDED	TOP AND BOT. UNSHIELDED	*
	A	B	C	D	E	F
			BEFORE THE STORM			
	22.51	12.36			14.00	12.10
		12.23			15.04	12.60
		12.00			14.42	12.20
		12.63			14.54	12.80
MEANS	22.51	12.30			14.50	12.43
			AFTER THE STORM			
	20.78	10.94	12.50	11.53	12.67	12.35
		11.11		12.05	12.70	11.75
					12.74	
					12.92	
					12.77	
MEANS	20.78	11.03	12.50	11.79	12.76	12.05

* (F above) Sides shielded, bottom unshielded, and 16 layers of lead on top.

The means of observations with the same apparatus in a tent on the campus of California Institute of Technology, Pasadena, are as follows in Table VII.

Table VII.

A	Unshielded	11.57
B	Shielded	9.37
C	Top only unshielded	9.54
D	Bottom only unshielded	9.40
E	Top and bottom unshielded	9.54
F	Both sides unshielded	10.75
G	Sides shielded, bottom unshielded, 16 layers of lead on top	9.28

Taking up the Pike's Peak data, we see, first, that there is no evidence of any difference in intensity of the penetrating radiations coming from the north and from the south, for the difference between the ionizations in Table V. when the north side was unshielded and when the south side was unshielded is well within the experimental error. The data shows, also, that most of the radiation entered the electroscope through the sides, as was to be expected.

Another interesting result is that on Pike's Peak, the radiation out-of-doors was greater than that in-doors, while in Pasadena the radiation out-of-doors is a little over 1 ion per cm^3. per sec. less than that in-doors. This indicates that at Pasadena the walls of the building add more radiation than they absorb from the outside, while on Pike's Peak the reverse was true. This is because on Pike's Peak there was more outside radiation to absorb.

The radiation found on Pike's Peak is of the right magnitude. If the amount of radiation from the ground be taken the same as on Mt. Whitney (3.7), then, following the same method as was used in connection with the Mt. Whitney data, the radiation which would have been observed at the altitude of Pike's Peak (4300 m.) if the ground had not contributed anything is, from A, Table V., 23.2 - 3.7 = 19.5 ions per cm^3 per sec. The difference between this and that observed at Pasadena, from A, Table VII., is 19.5 - 11.6 = 7.9 ions per cm.^{3} per sec. This is the difference between the amounts of radiation at 4300 m. and at the ground which should be observed in an airplane. On referring to Table II., it will be seen that this value fits admirably with the airplane data; it is also in agreement with the Mt. Whitney experiments.

3. THE INADEQUACY OF KOLHÖRSTER'S PROPOSED RADIATION

Kolhörster (Sitz. der Preuss. Akad. der Wiss., v.34, p.366, 1923) reports some experiments which had as their object the measurement of the absorption coefficient of the penetrating radiation. In the first of these experiments he lowered two electroscopes to various depths beneath the surface of both canals and lakes, and he found a continually decreasing amount of radiation as the electroscopes were lowered to greater depths. From these values he calculated an absorption coefficient. The data is given below.

CANALS

Depth of canal = 3 m.

Meters below surface	1.0	1.5
Decrease in ionization	1.6	2.2

Depth of canal = 4 m.

Meters below surface	1.3	2.2	2.9
Decrease in ionization	1.2	1.8	2.1

Meters below surface	0.8	1.5	2.5	2.9
Decrease in ionization	0.6	0.7	1.4	2.1

LAKES

Depth of lake = 6 m.

Meters below surface	1.1	2.4	4.4
Decrease in ionization	0.62	1.25	1.75

Depth of lake = 12 m.

Meters below surface	1.1	2.4	5.0
Decrease in ionization	0.48	1.24	2.08

This result agrees with some work of Gockel (Phys. Zeit., v.16, p.346, 1915) which is as follows:

Meters below lake surface	2	4	6
Decrease in ionization	0.6	1.7	2.7

Meters below lake surface	2	4
Decrease in ionization	1.66	3.6

The results of all experiments of this type are largely dependent on the radioactive content of the water.

Kolhörster also made measurements on glaciers in Switzerland. Here he observed the radiation at different distances within a cave cut into the side of the glacier which sloped in such a manner that increasing distances from the entrance meant increasing thicknesses of ice above the electroscope. From these results he calculates another absorption coefficient. The cave in which his measurements were made was 2 m. high and 1.5 m. broad, so that it was quite a large opening. He may, therefore, have been measuring only the decrease in radiation coming through the opening instead of the radiation coming through the thick layer of ice (15 m. in one case) as he supposed. If this were the case, he would, of course, find a continually decreasing intensity of radiation just as he did find when he went further into the cave.

A summary of his results follows:

ALTITUDE METERS	ABSORBER	ABSORPTION COEFFICIENT PER CM. OF WATER
40	Water	2.0×10^{-3}
2300	Ice	1.6×10^{-3}
3550	Air	2.6×10^{-3}
3550	Ice	2.7×10^{-3}
	MEAN	2.5×10^{-3}

Kolhörster quotes the absorption coefficient of Ra C per cm. of water at 3.9×10^{-2}. Chadwick places it at 4.7×10^{-2}. It is given in Hevesy and Paneth's "Lehrbuch der Radioaktivität" as 5.5×10^{-2}. McClelland finds the ratio of absorption coefficient to density equal to 3.4×10^{-2} and Soddy finds for this ratio 4.0×10^{-2}. Using the value assumed by Kolhörster, which is seen to be none too high, Kolhörster's absorption coefficient is less than 1/15 that of Ra C. The value for the absorption coefficient of Th D per cm. of water assumed by Kolhörster is 3.3×10^{-2}. Kolhörster's observed coefficient is only 1/13 of this.

Kolhörster states that there are probably 2 ions per $cm.^3$ per sec. at sea level which are of this penetrating kind. Unshielded on the steel stand at Pasadena, the radiation was 11.6 ions per $cm.^3$ per sec. Now if 2 of these are due to Kolhörster's penetrating radiation, $11.6 - 2 = 9.6$ are due to the intrinsic radiation from the electroscope and stand, and to the local radiation. The presence of the stand seemed always to increase the ionization by around 2 ions per $cm.^3$ per sec. When the electroscope alone was lowered to a depth of 2 m. below the surface of a reservoir, the mean of two observations gave 4.45 ions per cm^3 per sec.; this is taken as the intrinsic radiation from the electroscope itself. If this be subtracted from the value found on the surface of the lake (p.32), namely, 6.37, the result means a reduction of 1.92 which is in good agreement with the experiments of Kolhörster and Gockel reported above, and which is confirmed by a reduction of 2 ions per cm^3 per sec. found by Mr. G. Harvey Cameron and the author when the electroscope was lowered 3 m. into the Pacific Ocean at Avalon, Calif. The radiation from the electroscope is not more than 4.45 ions per cm^3 per sec., but may be less if the water in which the measurements were made was slightly radioactive. Subtracting from the 9.6 found above, the 2 which have their origin in the stand, there results 7.6 ions per cm^3 per sec. which are due to intrinsic radiation of the electroscope and to local radiation such as comes from the ground and from the atmosphere. The local radiation, then, lies between 7.6 - 4.45 = 3.15 and 7.6 , the latter being the correct value only if the electroscope contributes nothing to the ionization. In any case, the local radiation cannot possibly be more than 7.6 ions per cm^3 per sec., and if this local radiation proceeds from any known radioactive substance, not more than 1 of these can penetrate the 4.8 cm. of lead when the electroscope is completely shielded. Now, when the electroscope is completely shielded at Pasadena, the ionization is, from B, Table VII., 9.4 . Of these, part is assumed due to the Kolhörster radiation which gets through the lead; this part is $2e^{-4.8 \times 0.032}$ where 2 is the supposed amount of Kolhörster's radiation at Pasadena; 4.8 is the thickness of lead; and 0.032 is the absorption coefficient in lead of Kolhörster's radiation, found by multiplying the absorption coefficient of Ra C in lead by the ratio of the absorption coefficients in water of Kolhörster's radiation and the radiation from Ra C. Making the calculation indicated above, it is found that the amount of the assumed Kolhörster radiation getting through the lead at Pasadena is 1.7 ions per cm^3 per sec. This leaves $9.4 - 1.7 = 7.7$ which are produced by the radiation from electroscope, stand, and lead shields, and the local radiation. But it was found above that not more than 1 ion per cm^3 per sec., and probably much less, of the local radiation could get through the lead. There remain, then, at least $7.7 - 1 = 6.7$ which are the result of radiation from the electroscope, stand, and lead, when the electroscope is shielded.

On Pike's Peak, if we are to be most lenient, we shall use the values of the radiation observed after the storm. If the values obtained out-of-doors or in-doors before the storm were used, the present argument would be strengthened. From A, Table VI., the radiation with the electroscope unshielded on Pike's Peak after the storm was 20.8 . If it is the increase in Kolhörster's extra-terrestrial radiation that is observed in airplanes and balloons and on mountains, then <u>this</u> radiation is $20.8 - 11.6 = 9.2$ ions per cm^3 per sec. greater in amount on Pike's Peak than at Pasadena;

that is, the total radiation of this kind on Pike's Peak should be $9.2 + 2 = 11.2$ ions per cm.^{3} per sec. Of course, if most of the increase is not in Kolhörster's penetrating radiation, this radiation becomes of relatively little importance and another cause of the increase must be looked for. Of this assumed radiation of amount 11.2 ions per cm.^{3} per sec., $11.2e^{-4.8 \times 0.032}$ or 9.6 ions per cm.^{3} per sec should penetrate the lead. We found above that the intrinsic radiation from the electroscope, stand, and lead, when shielded was not less than 6.7 ions per cm.^{3} per sec. Therefore, if no local radiation got through the lead on Pike's Peak, at least $6.7 + 9.6 = 16.3$ ions per cm.^{3} per sec. should have been observed on the Peak when the electroscope was completely shielded. If some local radiation did get through, this value should have been greater. Actually, from B, Table VI., after the storm, an ionization of 11.0 ions per cm.^{3} per sec. was observed. The difference between these two values is entirely out of the range of experimental error. The only assumption made here is that the local radiation from the ground, etc., at Pasadena, proceeds from known radioactive substances.

The conclusion to be derived from this argument is that the observed increase in radiation in going from Pasadena to Pike's Peak does not come about through an increase in a penetrating radiation such as is proposed by Kolhörster.

4. THE CALCULATION OF ABSORPTION COEFFICIENTS

The radiation at high altitudes may be considered as coming from known radioactive substances. This may be shown by calculating absorption coefficients from the data already given, when the assumption is made that all the radiation is homogeneous, including that from the stand which is also cut out by the lead. It is desired to show that there is no necessity of believing either in a state of great heterogeneity in the radiation or in the existence of a radiation of any very abnormal penetrating power.

We will assume that the electroscope contributes 4.45 ions per cm^3 per sec. This was the value found when it was immersed in 2 m. of water. The correct value is less than this if it differs at all from the value assumed; if it is less, the argument which will be presented here will be strengthened.

We will take as the contribution of the electroscope, the stand, and the lead shield, when completely shielded, 8.6 ions per cm^3 per sec. This is surely as low as this figure should be placed, for the local radiation at Pasadena is most certainly not more than 7 ions per cm^3 per sec. and of these only 11% or 0.77 are able to get through the lead shield if this radiation has the absorption coefficient of Th D. Therefore, the electroscope, the stand, and the lead contribute at least $9.37 - 0.77 = 8.6$ ions per cm^3 per sec., for 9.37 is the value of the ionization found at Pasadena when the electroscope was shielded, and is equal to the sum of the local radiation getting through the lead and the contribution of the electroscope, the stand, and the lead.

Let λ be the absorption coefficient per cm. of lead. Then $I = I_0 e^{-\lambda d}$ where I_0 is the measured intensity of the radiation unshielded, I is the radiation that gets through the shield, and d is the thickness of the shield in cms. For seven layers of lead shielding, d was 4.8, and for three layers, 2.06 .

It is desired to calculate the absorption coefficient of the radiation external to the electroscope; I_0 is, therefore, found by subtracting 4.45 from the ionization observed when the electroscope was unshielded, and I is got by subtracting 8.6 from the ionization observed in the same location when the electroscope was shielded. For example, out-of-doors on Pike's Peak, $I_0 = 23.2 - 4.45 = 18.75$, and $I = 11.6 - 8.6 = 3.0$. λ may then be readily calculated. The resulting values of λ are given below.

Out-of-doors on Pike's Peak, $\lambda = 0.38$
In-doors on Pike's Peak before the storm, $\lambda = 0.33$
Indoors on Pike's Peak after the storm, $\lambda = 0.40$
Out-of-doors at Pasadena, $\lambda = 0.46$

The absorption coefficient of the gamma rays from RaC per cm. of lead is 0.50, and that of the gamma rays from Th D is 0.46 . The absorption coefficient given by Kolhörster on which he bases his belief in an abnormally penetrating radiation is per cm. of lead 0.032 .

It is evident that the conclusion to be drawn from the present investigation is in glaring contradiction to the views of Kolhörster. The gap is so wide that it seems impossible to reconcile the two view-points. It may be thought that this can be done by taking into account the way in which the absorption coefficients in this investigation are calculated. That is, these coefficients are average values, and it may be thought that they would result if the radiation measured were not homogeneous but a mixture of Kolhörster's radiation with a soft radiation. It is found, however, that no matter how high an absorption coefficient is assigned to this supposed soft radiation, in order to get an average coefficient of 0.38, Kolhörster's radiation could never be more than 19% of the total radiation exclusive of that which comes from the electroscope. This would make it an unimportant part of the whole, and it would still be necessary to identify the increase in radiation that occurs at high altitudes with an increase in the soft radiation.

It may be insisted that there are several factors which tend to make our calculated absorption coefficients too high, and it is desired to answer these arguments here. First, it may be said that inasmuch as the penetrating radiation comes apparently from all directions, some of the radiation which would enter the electroscope at an angle when unshielded would have to traverse a thickness of lead greater than that used in the calculations in order to be effective when the electroscope was shielded. This is true ; but a little consideration will show that it cannot possibly bridge the gap between the contradictory experiments. Most of the ionization is produced by rays which enter the electroscope at relatively small angles to the normal; those which enter at very large angles can pass through only a corner of the electroscope and are, therefore, unimportant. The rays which enter at 45 degrees to the normal are the worst ones that need be considered, and if all the rays entered at this angle, the absorption coefficient would only be reduced to seven-tenths the value given. This factor, therefore, cannot go a great way in reducing the calculated coefficients.

It may be urged that some observers have found absorption in lead to be not exponential. For example, to take a radical case, Tuomikoski reports the absorption coefficient of gamma rays in lead as varying from 0.7 to 0.25 when the thickness of lead traversed is varied from 0.4 cm. to 18. cm. All of these experiments, however, are seriously affected by spurious radiations. Mr. and Mrs. Soddy and A. S. Russell (Phil. Mag., v.19, p.725, 1910) found that absorption in lead was exponential when the brass electroscope was effectively shielded from these spurious radiations which seemed to be reflections by nearby objects of an incidence radiation from the shielding lead. The method of shielding in the present investigation would seem to be such that absorption should be exponential.

There are, as well, several factors present which would tend to make the calculated absorption coefficients too low. If there were, with the experimental disposition used, more secondary radiation than is present in ordinary absorption measurements, the primary radiation would appear more penetrating than it really was. this factor might exist, for the shields were close to and completely surrounded the electroscope. Furthermore, it is to be remembered that in the calculation of the absorption coefficients very conservative assumptions were made; if different , but not unreasonable, values be assumed, the coefficients may be increased by 0.01 to 0.02 .

It is concluded from this portion of the investigation that the so-called "penetrating radiation" does not differ greatly from the gamma radiation proceeding from known radioactive substances.

5. THE EFFECT OF THE STORM

The snow-storm here referred to started about six o'clock in the evening and lasted most of the night. It was accompanied by a very strong wind blowing from the mountains on the west to the valley on the east. Observations corresponding to those which had been made before the storm continued up to twenty-eight hours after the effect of the storm was first noticed. The effect of the storm may be seen by reviewing Table VI. All observations after the storm gave less amounts of radiation than corresponding observations before the storm. The differences are entirely out of the range of experimental error, and are much greater than the ordinary variations observed. This effect is given some slight confirmation by the observations out-of-doors during which it snowed lightly several times. In these cases, however, the reduction was never so definite and long-lived; but this may be attributed to different wind conditions and to the presence of the fallen snow. Strong (Phys. Rev., v.27; p.39, 1908) also found a decrease in the amount of radiation after a snow-storm, the resulting low value being maintained for eighteen hours when the observations were apparently discontinued. He attributes it to the sweeping from the atmosphere of part of the radioactive products emitting the observed gamma rays. Evidence for this view is found in the experiment of C. T. R. Wilson (Proc. Camb. Phil. Soc., v.11, p.32) in which freshly fallen snow was reported radioactive.

If we accept this explanation of the reduction in the intensity of the radiation, it may be thought that during the storm and for a little while after, the radiation should have increased in amount because of the presence on the ground of the radioactive material brought down by the snow. This is not to be expected, however, because the snow that fell on the ground was shielded from the electroscope by the thick rock walls of the building, and the snow that fell on the flat roof above was immediately swept off by the violent wind that was blowing outside. This wind continued throughout all the rest of the observations and may account for the radiation not returning to its former intensity before observations had to be discontinued. This might be expected because the wind was blowing from the direction of the snow-covered Rockies and therefore probably brought with it very little radium emanation.

The most interesting effect of the storm is the reduction made in the amount of radiation observed when the electroscope was completely shielded. This reduction means that the part which gets through the lead is dependent on the conditions existing in the atmosphere, and is a further indication that *there is no very penetrating radiation which, coming from outside the atmosphere would be practically independent of conditions near the earth*. The experiment shows that *if there is any heterogeneity in the radiation, even the hardest is of local origin, probably coming from radio-active products in the atmosphere*.

Of course, there is still the possibility that some inexplicable change in the working of the electroscope took place at just the proper time; but this is most improbable inasmuch as the electroscope seemed to be working perfectly at the time, and gave the same results in Pasadena after the trip as had been found before. It would be interesting to repeat the experiment, but it would be difficult because nature must be depended upon to reproduce the conditions.

VI. THE SOURCE OF THE PENETRATING RADIATION

Discounting the possibility of the radiation arising through an entirely new process yet undiscovered, there are only two possible sources of the radiation:- radioactive products in the atmosphere, and the heavenly bodies.

Kolhörster favors the view of a source external to the earth, and in his last paper reports his experiments as indicating a radiation from the Milky Way. It would seem, however, that bodies at the great distance of the Milky Way from the earth would have to be ridiculously dense in radioactive substances in order to produce at the earth a radiation of the observed amount. Some idea of the enormous radioactivity necessary may be got from the calculation of E. v. Schweidler (Elster - Geitel Festschrift, pp. 411 - 419) that if the sun and the moon were the cause of the penetrating radiation, they would have to be 170 times as radioactive as uranium. Nernst suggests that only the nebulous stars of small density could be active because, since radioactive substances are very dense and would therefore be found mostly in the interior of the star, the radiation from these substances would, in the case of dense stars, be all absorbed before it got out. Even in the case of stars of small density, the concentration of radioactive substances in the interior would make necessary a much greater quantity of these substances than if they were on the surface. Aside from this objection, the absorption experiments of Prof. R. A. Millikan and the author are incompatible with the hypothesis of an external source in explanation of the increase in radiation with altitude, for the rate of increase in the intensity of radiation with increase in altitude demands an absorption coefficient for the radiation which is far too low to agree with our observed coefficients.

If the source of the radiation is radioactive substance in the earth's atmosphere, it is probably either radioactive dust or the disintegration products of Ra emanation and Th emanation. If radioactive dust were the cause, it is shown by K. Bergwitz (Meteor. ZS., v.33, p.310, 1916) that if the dust is not accredited with abnormally high radioactivity, it would have to be so dense that optical trouble would result.

The other possibility is also faced with difficulties. Eve (Phil. Mag., v.21, p.26, 1911) calculates from the measured quantities of Ra C and Th D in the atmosphere that the gamma rays from these substances should not produce more than 0.06 ions per cm^3 per sec. Also, Hess (Phys. Zeit., v.14, p.610, 1913) calculated the amount of Ra C in the atmosphere necessary to produce the observed penetrating radiation at an altitude of 1000 - 2000 meters, and found it to be twenty times that at the earth's surface. Making a calculation similar to the one for the atmosphere, Eve finds that the gamma rays from radium and thorium in the earth should not exceed 1.6 ions per cm^3 per sec. This is obviously much too small for we find at least 3 ions per cm^3 per sec. less over water surfaces than over land. If the calculation for the earth cannot be relied upon, it casts doubt on the validity of the calculations for the atmosphere.

If we could believe that there is enough radium and thorium emanations in the atmosphere at sea-level to produce the observed radiation, things would not be so bad. For Flemming (Phys. Zeit., v. 9, p.801, 1908) found from balloon observations at 3000 m. that the same amount of active deposit could be collected as at the surface of the earth. Saake (Phys. Zeit., v.4, p.626, 1903) and Gockel (Phys. Zeit., v.8, p.701, 1907) did better than that and found the amount collected at high altitudes greater than that collected at sea-level. Wright and Smith's measurements (Phys. Zeit., v.15, p.31, 1914), however, give the content at Manila as 85×10^{-18} Curie per cm^3 and on Mt. Pauai at an elevation of 2460 m., 19×10^{-18} Curie per cm^3. These measurements are undoubtedly affected greatly by wind conditions. Considering all the evidence, the indication is that the radium and thorium emanation contents of the atmosphere do not decrease in amount as one goes to higher altitudes, in the way that is to be expected if the emanations start from the earth. Bongards (Phys. Zeit., v.24, Jan. and July, 1923) has recently proposed a theory in which most of the emanation present in the atmosphere is born to the earth by a mass radiation from the sun. His evidence is of three kinds:- 1. He finds that the Ra emanation content varies with the same periodicity as the rotation of the sun. 2. He notices a relation between the Ra emanation content of the atmosphere and the presence of calcium clouds on the sun. 3. Relative values of emanation content determined by Bongards in Germany and by Smith and Wright in Manila on the same days agree although they used different methods. However the emanation gets to the high altitude, if there is enough of it, it offers an explanation of the experiments on Pike's Peak.

The source of the so-called "penetrating radiation" is obviously still a matter for debate; but it is hoped that this research will, in time, prove to have simplified the problem or to have stimulated further investigation which will, in the end, lead to its solution.

VII. SUMMARY

1. By observations in airplanes and in captive balloons, it is found that the so-called "penetrating radiation" first decreases to a minimum, then increases continuously. Observations were made to an altitude of 5340 m.

2. The rate of increase of the radiation with altitude was not so great as that found by Kolhörster.

3. The apparent increase of the radiation with altitude was not due to an increased insulation loss which resulted from the lowered temperature, as was suggested by Kunsman. The electroscope showed no such effect of temperature, and if it had, the guard ring would have eliminated most of the insulation loss.

4. Observations on Mt. Whitney at elevations of 4130 m. and 3660 m. were found to agree well with the airplane observations. From measurements of the radiation over a lake at 3660 m., it is concluded that the increase in radiation on Mt. Whitney over that in Pasadena is not due to a greater radioactivity of the rocks on Mt. Whitney, but comes from the atmosphere or beyond.

5. Continuous observations for 40 hours at an elevation of 4130 m. on Mt. Whitney failed to show any regular difference between the night and day radiations, and it is concluded that the radiation measured cannot be a primary radiation from the sun.

6. From observations on Pike's Peak (elevation 4300 m.),

in which lead shields 4.8 cm. thick were used to absorb the radiation, it is concluded that the observed increase in radiation in going from Pasadena to Pike's Peak does not come about through an increase in a penetrating radiation (with absorption coefficient 1/15 that of Ra C) such as is proposed by Kolhörster.

7. From the same observations, it is concluded that the so-called "penetrating radiation" does not differ greatly from the gamma radiation proceeding from known radioactive substances.

8. The main part of the radiation cannot come from outside the earth's atmosphere for the absorption coefficient calculated from the rate of increase of the radiation with altitude is much lower than that which was observed on Pike's Peak.

9. From the effect of a snow-storm which occurred during observations on Pike's Peak, it is concluded that all of the radiation is of relatively local origin.

In conclusion, the author desires to thank Prof. R. A. Millikan for suggesting the problem, and for his kindly interest and advice throughout the progress of the work. The author is also indebted to Mr. G. Harvey Cameron for his assistance in making the absorption measurements in Pasadena, and to Prof. P. S. Epstein, Mr. I. S. Bowen, and Mr. Lewis M. Mott-Smith who made the trip to Mt. Whitney with the author, valiantly sharing the burdens of that expedition. To the friendly cooperation of the officers of the U.S. Army Air Service the author owes what success attended the

experiments in airplanes and in captive balloons. No experimental work can be done without an apparatus, and for a good apparatus I am grateful to Mr. Julius Pearson, Head Instrument Maker.

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May 28, 1924.

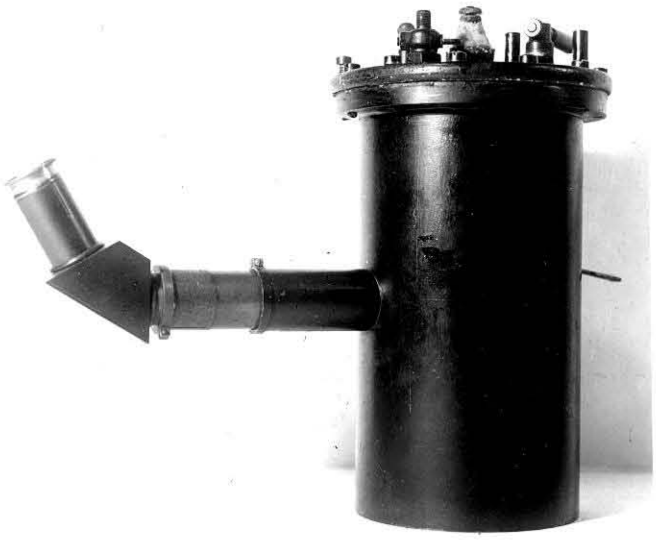

Fig. 1

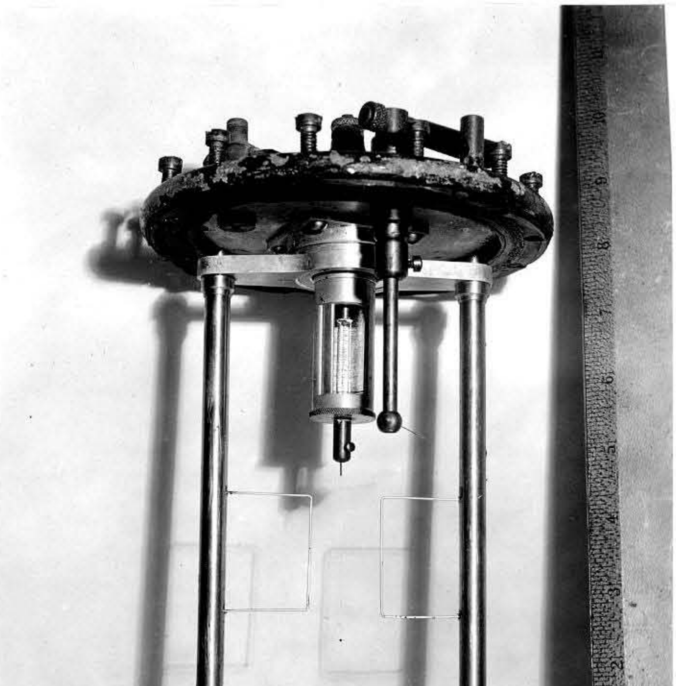

Fig. 2

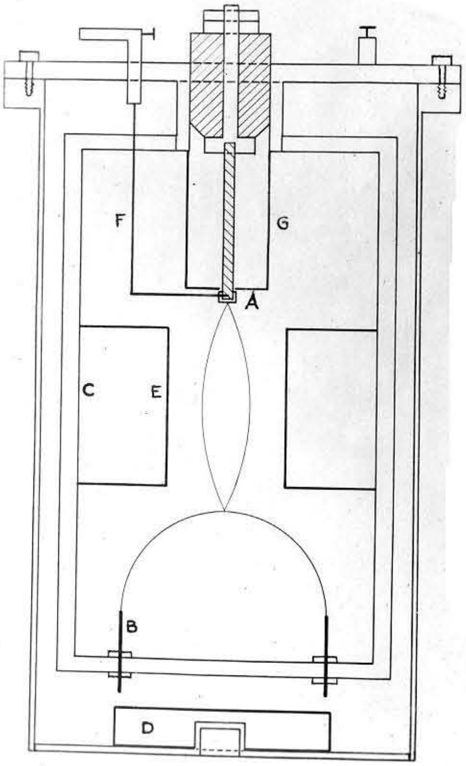

Fig. 3

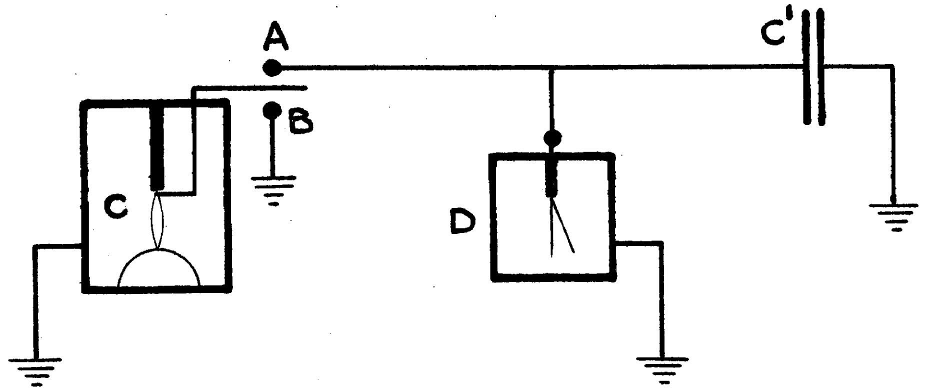

Fig. 4

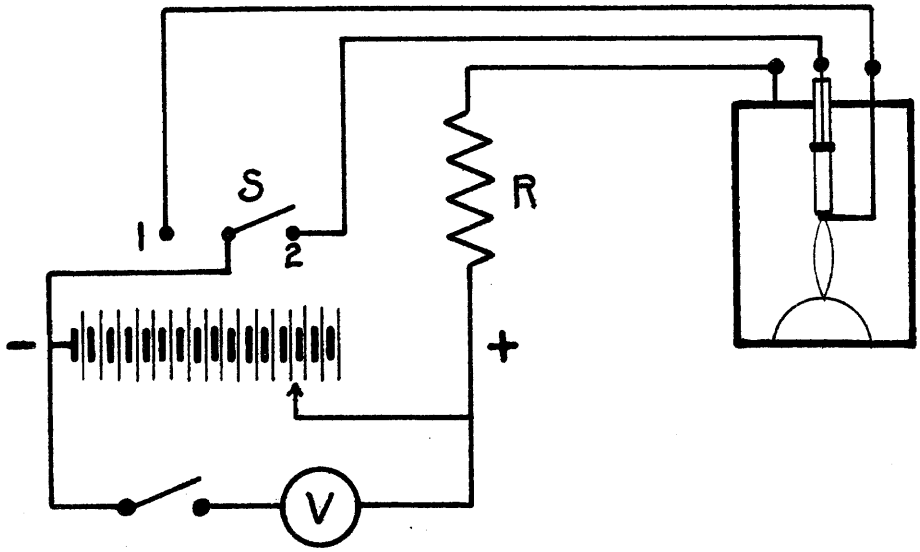

Fig.5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11