THE RESIDUAL IONIZATION IN AIR AT NEW HIGH PRESSURES, AND ITS RELATION TO THE COSMIC PENETRATING RADIATION[1]

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Abstract

Measurements of the residual ionization in air were made with a new spherical chamber of 13.8 liters capacity at pressures up to 170 atm., at an altitude of 5400 ft. Lead and water shields were used. The slopes of the ionization-pressure curves continued to decrease at the higher pressures, becoming zero in the neighborhood of 130 to 140 atm. The ionization-pressure relation and the effects of shielding are explained on the basis of the production of ions solely by secondary radiations excited in the walls of the vessel by the cosmic penetrating radiation. The theoretical consequences of such an assumption are discussed.

Measurements of the residual ionization in several gases contained in a large chamber at pressures up to 80 atmospheres, were made a few years ago by the writer[2] and other students[3] of Professor Swann. These experiments showed that the primary ionization due directly to any very penetrating radiation was considerably less than that which would correspond to the residual ionization at atmospheric pressure. However, the observed increases in ionization per atmosphere increase in pressure at the highest pressures were usually of the order of magnitude of the ionization at atmospheric pressure attributed by other experimenters to the cosmic penetrating radiation. Later, in 1926, Swann[4] found that the ionization at all pressures up to 68 atmospheres increased with altitude in accordance with the theory that a primary cause of the ionization consists of an ultrapenetrating radiation having its origin outside our atmosphere.

In order to investigate further the residual ionization and particularly its relation to the cosmic radiation, a new ionization chamber[5] was constructed and arrangements made for rather elaborate shielding.

Apparatus and Materials

The chamber was formed by excavating a spherical cavity 11-23/32 inches in diameter from a cylindrical, nickel-steel ingot 15-1/8 inches in diameter and 17-3/8 inches long. The volume occupied by the air under investigation was

[1] Reported at the Cleveland meeting of the American Physical Society, December, 1930.
[2] J. W. Broxon, Phys. Rev. **27**, 542 (1926).
[3] K. M. Downey, Phys. Rev. **16**, 420 (1920); **20**, 186 (1922); H. F. Fruth, Phys. Rev. **22**, 109 (1923).
[4] W. F. G. Swann, J. Frank. Inst. **209**, 151 (1930).
[5] J. W. Broxon, J.O.S.A. and R.S.I. **18**, 403 (1929).

13805 cc. The central electrode, guard system and ebonite insulation were incorporated in the form of cones in a plug which was seated upon a narrow fiber gasket. This chamber sustained a hydraulic test pressure of 5000 lbs. per sq. in. for half an hour with no indication of weakening.

The chamber was mounted approximately in the center of a wooden tank 14 ft. in diameter and 13.5 ft. high, in the basement of Macky Auditorium at the University of Colorado, Boulder, at an altitude of 5400 ft. and latitude 40°N. The chamber could be surrounded by a cylindrical lead shield 2 in. thick. This could be covered by a water-tight hood 2 ft. in diameter and 2 ft. high, and surrounded by water. The photograph, Fig. 1, shows the ionization chamber with the hood removed and part of the lead shield in position. A Brown recording thermometer bulb was inserted in a small hole drilled about 4 in. into the bomb near its base, the entire instrument being insulated carefully at the potential of the bomb. The connection with the central electrode was effected by means of a wire stretched along the axis of a 2 in. pipe.

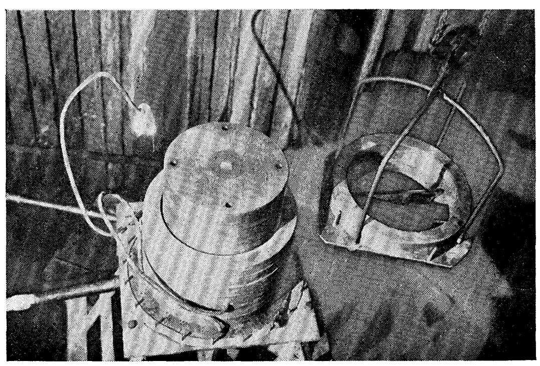

Fig. 1. Photograph of apparatus.

The air used in these measurements was dried, freed from dust, and allowed to age at least 4 weeks in each instance.

The ionization chamber was never allowed in any building which had contained radioactive supplies. Care was also taken that the shields be as free as possible from radioactive contamination. The lead shield was cast from discarded overhead telephone cable sheaths. The water used was the city tap water. The source of the Boulder city water consists entirely of surface water from the Arapahoe Glacier and snow deposited between the altitudes of 10200 and 13500 feet. This is brought down to the city through iron pipes which are nowhere imbedded to any appreciable extent. While making a survey of the radioactive waters of Colorado several years ago, Dean O. C. Lester tested the Boulder city water and was unable to detect any radioactive content. The ionization currents measured provide evidence that the ionization chamber and shields were rather unusually free from radioactive contamination.

The pressures were measured by means of an American-Schaeffer and Budenberg gauge, calibrated by the U. S. Bureau of Standards. The applied compensating potentials were measured by means of a Jewell Instrument

Company voltmeter calibrated at a few voltages by the Bureau of Standards and over the entire scale in our own standardization laboratory by means of a standard resistance and potentiometer. The induction coefficient of the auxiliary or compensating condenser was measured by a null method of mixtures, the electrometer being used as the indicator and the comparison being made with a new variable standard air condenser constructed by Günther and Tegetmeyer. Comparisons were made with six different settings of the standard condenser. The average of these gave 26.3 cm as the induction coefficient of the compensating condenser relative to the central system, a value agreeing fairly well with an approximate calculation from the dimensions of the condenser. The corresponding induction coefficient of the ionization chamber was found to be about 4.5 cm at local atmospheric pressure.

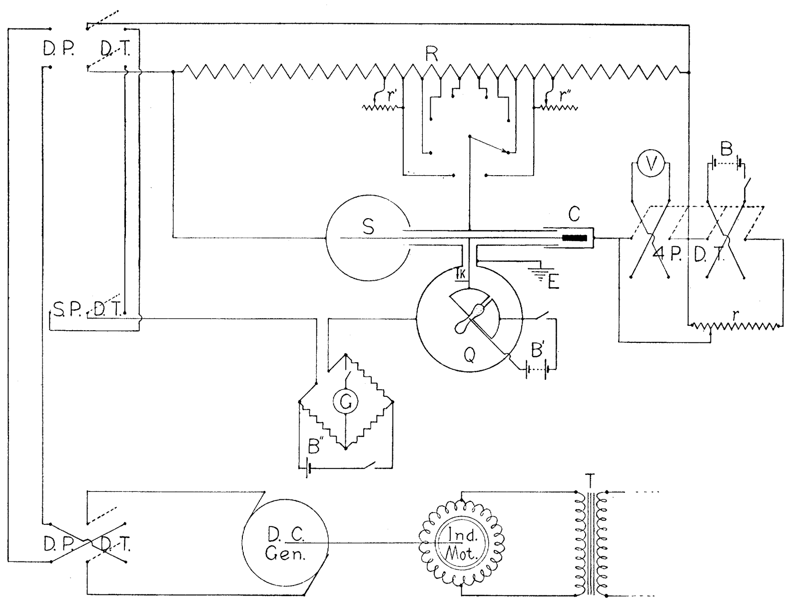

Fig. 2. Diagram of electrical arrangement.

Procedure

As shown by the wiring diagram, Fig. 2, the same sort of arrangement was employed in measuring the ionization as in the former investigations. The Wheatstone bridge was incorporated for the purpose of determining the dielectric constant of the air as discussed elsewhere.[6] The method of ionization measurement has been described carefully, particularly by Swann.[4] Distinct advantages of the arrangement consist of the provision for electrical shielding, eliminating almost entirely the possibility of effects due to the solid dielectrics, and the employment of the electrometer merely as an indicator, thus eliminating effects due to possible changes in sensitivity. In the present in-

[6] Reported at the meeting mentioned in note 1. The complete report constitutes the succeeding paper of this issue.

stance, the auxiliary condenser was fixed and the compensating potential was applied to this rather than directly to the ionization chamber. Thus the rate of application of the compensating potential was directly proportional to the ionization current whereas with the other arrangement the change in the induction coefficient of the ionization chamber relative to the central system with variation in pressure of the gas must be considered.

On account of inductive effects, the detailed construction of a guard system is very important. Termini of the system used here are shown in Figs. 3 and 4

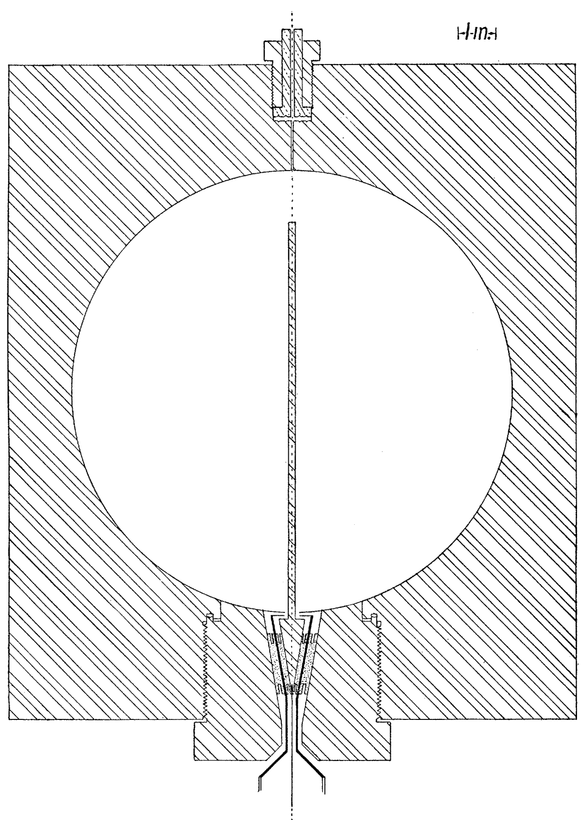

Fig. 3. Longitudinal section of ionization chamber.

which represent longitudinal sections of the ionization chamber and the auxiliary condenser, respectively, drawn approximately to scale. This system proved to be very satisfactory. Because the guard system in this case was necessarily in electrical contact with the earth, particular care had to be taken to insulate all other portions of the set-up from earth, including the sources of e.m.f.

Of course, it was exceedingly important to ascertain that saturation currents were being measured. No appreciable decrease of the ionization current could be detected when the applied P.D. was decreased about 20 percent when the largest currents were being measured at the highest pressures.

Therefore it is considered certain that saturation currents were measured throughout. It should be noted in this connection that although the high pressures necessitated low mobilities, the largest ionization currents were very small and hence practical[7] saturation was not difficult to establish.

When tests were to be made the air was admitted slowly into the ionization chamber to a maximum pressure of about 170 atmospheres. If measurements were made immediately after filling, larger values were obtained than after the establishment of equilibrium conditions. Therefore, from two to six

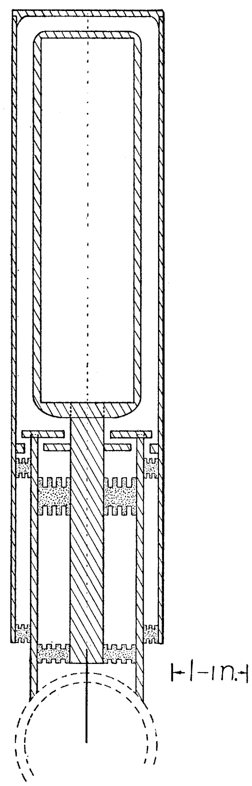

Fig. 4. Longitudinal section of compensating condenser.

hours were always allowed to elapse after filling the chamber before measurements of the ionization were begun. After three or four measurements, each over about an eight minute interval, had been taken at a given pressure, the pressure was usually decreased by three to six atmospheres at the higher pressures. Then at least half an hour was allowed to elapse before any measurements were taken at the lower pressure. Extension of this period to several hours in some instances had no effect. The gas leak was slight, although it was found necessary to remove the bomb and tighten the large plug after making two or three sets of observations.

[7] L. H. Gray, Proc. Roy. Soc. **A130,** 524 (1931); pp. 527–528.

Observations

The observations have been represented graphically. In Fig. 5 the ionization current in ions/cc·sec has been plotted against the total pressure in at-

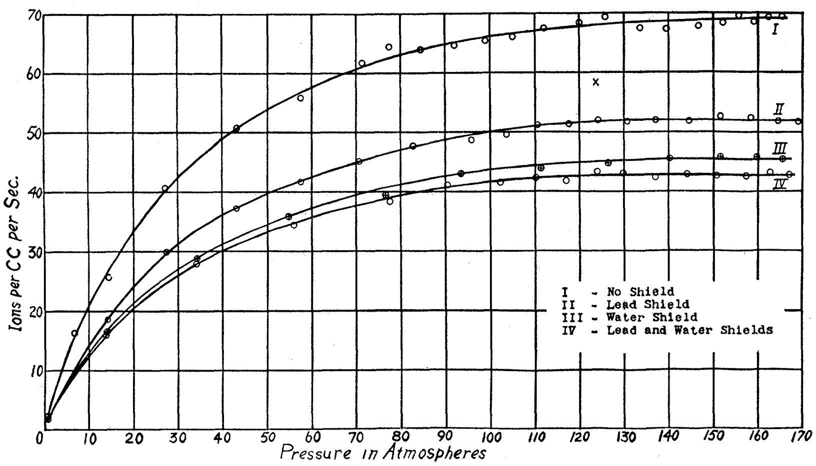

Fig. 5.

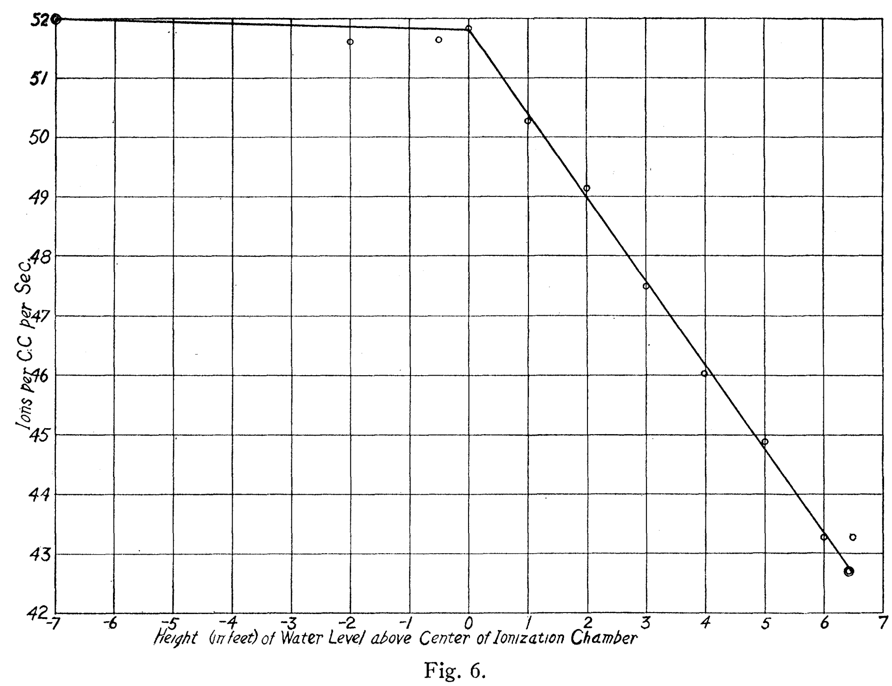

Fig. 6.

mospheres at 18°C. It may be worth mentioning in this connection that the slopes of the curves are so small in the region where the departure from Boyle's law is considerable, that if the ionization is plotted against the gas density instead of the pressure, the curves obtained are scarcely distinguishable from those shown here. Curve I was obtained with no shielding other than that provided by the heavy steel walls of the ionization chamber, by the building, and by the atmosphere. Curve II was obtained with the chamber surrounded by the 2-in. lead shield; curve III, with no lead shield but with the tank filled with water; and curve IV, with both the lead and water shields in position. The ionization current in each instance was measured at pressures between atmospheric pressure and about 170 atmospheres. At the higher pressures observations were made at shorter intervals than in the lower pressure region previously investigated.

The data represented by the curve of Fig. 6 were obtained with the lead shield in position and with the air in the bomb maintained at pressures between 166 and 169 atmospheres. Here the ionization was again plotted along the ordinate axis, but the abscissae represent the position of the surface of the water in the tank. Depth of the water level beneath the center of the bomb is designated by negative values, and height of the water level above the center of the bomb is designated by positive values. The end points designated by two concentric circles represent data recorded in Fig. 5. The one representing no water in the tank gives the maximum ionization of curve II, while the one representing the tank filled with water gives the maximum ionization of curve IV.

Discussion

One rather striking feature of the measurements is the very low value of the ionization measured in each case at the local atmospheric pressure. These values varied from 2.26 with no shield to 1.45 ion/cc·sec with both shields, at 0.82 atm. and 18°C. The smallness of these values together with the fact that the percentage decrease in the ionization due to shielding was in each instance only slightly less at atmospheric pressure than at the highest pressures, indicated that the ionization chamber, itself, was remarkably free from radioactive contamination.

The ionization-pressure curves resemble those obtained previously, over the pressure range of the earlier observations. In particular, there is a close correspondence between curve II, Fig. 5, and the curve obtained by Swann[4] with a similar lead shield at Colorado Springs at about the same altitude. The ratio of his values to those of curve II at corresponding pressures is 1.87 at 100 lbs./sq. in., but decreases to 1.32 at 500 lbs./sq. in. and then only to 1.29 at his maximum pressure of 1000 lbs./sq. in. or about 68 atm. His larger values at low pressures are probably due mostly to a slight radioactive contamination of the older chamber, while the nearly constant ratio at the higher pressures is of about the magnitude to be expected when the increased shielding provided by the heavier walls of the bomb and the building in the present instance is considered. Obviously, a better method of comparison is one based upon the *differences* between the absolute values of the ionization observed in the two instances at corresponding pressures. Thus there is an increase of only about 1.7 ion/cc·sec in this *difference* in the pressure interval from 500 to 800 lbs./sq. in., and practically no further variation at higher pressures. At the higher pressures, then, where the effects of chance radioactive contaminations become inconsequential, the forms of the curves become identical, showing a remarkable agreement between the two independent investigations.

The most interesting portions of the ionization-pressure curves lie in the new pressure range. In every case the pressure rate of increase of ionization is seen to have continued to decrease at the higher pressures, and the slopes of the three curves obtained with the chamber shielded are zero at pressures above about 130 atm. In curve I there appears to be a possible continued slope of about 0.04 ion/cc · sec · atm. at the highest pressures, but in the other three curves the slopes at the high pressure ends certainly are not greater than 0.02 ion/cc · sec · atm. over a range of 40 atmospheres, and probably are considerably less.

It would appear, then, that the immediate cause of the ionization was a radiation which was almost entirely absorbed at a pressure of 130 atm. If the source of this radiation were in the gas itself, the ionization should have continued to increase with the pressure. If the source were outside the chamber, either it would have been absorbed entirely by the shields or it would not have been absorbed considerably by the gas. Presumably, then, the source of the ionizing radiation was in the walls of the ionization chamber.

That the primary cause of the ionization was a much more penetrating radiation is shown by the continued decrease in the ionization produced by successively greater shielding. It seems that the situation might be explained, then, by the assumption that the primary cause of the ionization in the cases of the three lower curves was a very penetrating radiation which excited in the walls of the vessel a softer radiation, perhaps recoil electrons, and that the ionization was almost entirely due to this secondary radiation. That none should be excited in the gas, itself, seems remarkable in view of the amount of air present in the chamber at the high pressures, but if any appreciable portion of the secondary radiation were to originate in the gas, surely the ionization would continue to increase with the pressure to a correspondingly appreciable extent at all the pressures.

That the source of the radiation capable of penetrating the lead shield was above the level of the chamber is shown clearly by Fig. 6. Apparently, local gamma-radiations were practically entirely absorbed with the lead shield in position, since variation of the water shield below the level of the chamber had very little effect in this case. That local γ-radiations did contribute to the ionization with the chamber unshielded, is shown by the value, 58.21 ions/cc · sec, designated by an x in Fig. 5 and measured with no lead shield but with the water tank filled to the center of the bomb.

Absorption coefficient of the primary radiation

The decreases in ionization produced by the shields were of sufficient magnitude to give fair estimates of the average absorption coefficients of the primary radiation in the materials used. As has been pointed out, the ionization recorded in the shielded curves at the high pressures may be considered to be due entirely to the penetrating radiation. The maximum values of the ionization in curves I, II, III and IV are 69.14, 52.00, 45.43 and 42.60 ions /cc·sec, respectively. In the case of the lead shield, if we assume exponential absorption and disregard obliquity, we have for lead $\mu=[\log_e(45.43/42.60)]/5.08=0.0127$ cm^{-1}. Proceeding similarly in the case of water, we obtain $\mu=[\log_e(50.38/42.60)]/166=0.0010$ cm^{-1}. In this case, the thickness of the water shield has been taken as the 5.45 ft. depth of the top of the hood beneath the highest level of the water, and the initial intensity as that measured with the water level at the top of the hood, which would be correct if the radiation were directed entirely vertically.

In the case of the water shield we may calculate an upper limit for the absorption coefficient by assuming that the radiation approached the chamber uniformly from all directions above the horizontal. In the case represented by Fig. 6, the decrease in ionization was produced by horizontal disks of water placed above the chamber. If P is a point on the axis of a *thin* disk of thickness t and radius a, at a distance x from the disk, while the total intensity of all radiation originally approaching P through the solid angle 2π on the side next the disk is I_0, then the intensity of the radiation arriving at P after having passed through the disk is

$$I_d = I_0 \int_0^{\tan^{-1}(a/x)} e^{-\mu t \sec\theta} \sin\theta d\theta = I_0 \int_1^{(1+a^2/x^2)^{1/2}} y^{-2} e^{-\mu t y} dy.$$

The latter integrand may be expanded into a series which is uniformly convergent in the region designated. When this is integrated and terms involving powers of t higher than the first are discarded, the value obtained is

$$I_d = I_0[1 - (1 + a^2/x^2)^{-1/2} - \mu t \log_e (1 + a^2/x^2)^{1/2}].$$

Now $2\pi[1-(1+a^2/x^2)^{-1/2}]$ is the solid angle subtended by the disk at P. Therefore, $I_0[1-(1+a^2/x^2)^{-1/2}]$ is the intensity of the radiation which would have approached P through the solid angle subtended by the disk if the disk had been absent. Therefore, the decrease in intensity of the radiation arriving at P due to the presence of a disk of radius a and thickness dx at a distance x, is

$$-dI = \mu I_0 \log_e (1 + a^2/x^2)^{1/2} dx.$$

Then when the ionization chamber is so situated that its dimensions are small in comparison with both a and x, the slope of the absorption curve obtained by shielding with disks in the above manner is

$$-dI/dx = \mu I_0 \log_e (1 + a^2/x^2)^{1/2}.$$

If from Fig. 6 we take the values $I_0=42.6$, $-dI/dx=9.1/196.6$, $a=7$ and $x=6.45$, we obtain $\mu=0.0028$ cm^{-1}. This, of course, merely represents an upper limit for the average μ in water, just as the value first calculated represents a lower limit. Due to the absorption of the walls of the building and to the great absorption of the atmosphere in directions approaching the horizontal, the penetrating radiation would be much more intense in the vertical direction providing it entered the atmosphere with uniform intensity in all directions.

The values obtained for the average absorption coefficients agree quite well with those obtained by others[8] for the cosmic radiation. It should be emphasized, however, that this investigation was not planned for the purpose of determining coefficients of absorption, and does not permit their accurate evaluation. It is chiefly because the values obtained might be expected to be of the right order of magnitude, and because they do agree with values yielded by experiments designed primarily with this end in view, that they are mentioned. The approximations show quite unequivocally that the prime ionizing agency consisted of the "cosmic penetrating radiation."

Explanation of the ionization-pressure relation

In a former paper[9] the author deduced I–P relations which would follow from various assumptions as to the origins and characteristics of the ionizing radiations. The rather complicated combination chosen to represent the experimental curves was necessitated largely by the fact that the ionization passed through a minimum as the size of the chamber was varied. As has been pointed out, it appears that the ionizing radiations in the present instance must have originated in the vessel walls. This would necessitate a continuous increase in ionization with decrease in the size of a thick-walled vessel, because of the corresponding increase of the ratio of area to volume. In view of the present measurements it is strongly suspected that the variation of ionization with size of vessel obtained in the former experiments depended partly upon a chance radioactive contamination of the outer, high-pressure chamber. In the case of the two smaller containers which were constructed at the same time under the same conditions, the ionization increased with decrease of size.

Let us now make some very simple assumptions which can only be expected to lead to a very rough approximation of the observed relation. Suppose the ionization to have been due entirely to recoil electrons generated uniformly throughout the walls of the vessel by the cosmic radiation. Suppose further that these were all emitted in directions normal to the spherical surface (an exceedingly crude assumption) and were absorbed linearly both in the vessel walls and in the gas. As a preliminary step in the investigation of the variation with pressure of the ionization which would be produced under such circumstances, let us consider a still simpler case.

If we plot the ionization per cm of path of a homogeneous beam of linearly absorbable, parallel rays against the distance from their origin, we obtain a straight line. The intercepts of this line upon the coordinate axes respectively represent the maximum or initial ionization per cm of path along the beam, and the range of the beam or the distance from the origin within

[8] V. F. Hess, "The Electrical Conductivity of the Atmosphere and Its Causes," p. 138.

[9] J. W. Broxon, Phys. Rev. **28**, 1071 (1926).

which total absorption occurs. The area of the right triangle enclosed by the straight line and the coordinate axes represents the total ionization which the beam can produce. Also, the portion of the area of this triangle which is included between the ionization/cm axis and a normal to the distance axis at any point represents the ionization produced within that distance from the origin.

Suppose, for some reason, we should want to deal with the ionization due to a precisely similar beam after it had traversed the first quarter of its range. Everything would be represented as in the previous instance by a right triangle formed between the coordinate axes and a straight line. This triangle would also have the right angle at the coordinate origin and would be similar to the first one in every respect, but corresponding dimensions would be just three-fourths as great as in the first instance. If we desired to deal with a similar beam after it had traversed the first half of its range, we should obtain a similar triangle with dimensions half as great as in the first instance. If three-fourths of the range had been traversed, the similar triangle would have dimensions only a quarter as great as the first, etc. If, then, we were to have all four of the above mentioned beams starting normally from a certain plane such as the inner surface of an ionization chamber, and ionizing simultaneously, we might represent the ensuing ionization by means of the four triangles, piling them one upon the other. If they were cut from pieces of paper and fitted upon the coordinate axes in the proper manner in the order of decreasing size, a sort of pyramid would be formed. The total volume of the the paper pyramid could then be considered to represent the total ionization produced by the four beams. Moreover, the volume included between a plane normal to the distance axis at the origin and another normal to the distance axis at any given distance from the origin would represent the ionization produced by the four beams within that distance from the surface of origin of the beams.

If the ionizing radiation in the present investigation originated throughout the walls of the ionization chamber and proceeded normally to the inner surface in the simple manner that has been postulated, it would not be homogeneous upon entering the chamber, but the corpuscular velocities would be distributed practically uniformly between zero and a maximum. In other words, we might consider that at the inner surface the beam would consist of an enormous number of similar parallel beams with the then untraversed portions of their ranges distributed uniformly between zero and a maximum for electrons just starting at the inner surface. The ionization in this case, then, could be represented by a pyramid similar to the one above, but with the steps smoothed out. Or the entire pyramid might be thought of as being compressed into the base triangle, forming a right triangular mass with a density varying directly as the distance from the hypotenuse, the line which would represent the variation with distance from the inner surface, of the ionization/cm due to a homogeneous beam of electrons originating at the inner surface. If, then, we think of a triangle endowed with mass and with a density varying in the above manner, we need only change from area to mass in order to change from a homogeneous beam to a nonhomogeneous beam of the above type. This procedure appeals to the writer as preferable to continuing with the pyramid. The intercept, a, on the ionization/cm or y-axis may be considered to represent the ionization per cm of path due to a corpuscle of maximum velocity, and the intercept, b, on the distance axis, to represent the maximum range. The total mass of the triangle would represent the total ionization which could be produced by all the electrons entering the chamber. Also, the mass of the portion of the triangle included between the ionization/cm axis and a normal to the distance axis at any point would represent the ionization produced by the nonhomogeneous radiation within that distance from the surface of entrance of the radiation into the chamber.

In the present instance, if tertiary radiations, etc., be disregarded, the ionization recorded at any pressure would represent the ionization produced within an effective distance from the wall approximately equal to the product of the inner diameter of the chamber and the pressure, and hence approximately proportional to the pressure. Hence we may consider the pressure, P, to represent distance in the present case.

If we write the equation of the hypotenuse of the triangle in the form

$$mP - y + a = 0,$$

where $m = -a/b$, the normal distance from the hypotenuse to any point (P, y) within the triangle is equal to $(mP-y+a)/(m^2+1)^{1/2}$.

Therefore, we may express the ionization, I, at pressure P in the form

$$I = k/(m^2 + 1)^{1/2} \int_0^P dP \int_0^{mP+a} (mP - y + a)dy$$

$$= \left[ka^2/6b(a^2 + b^2)^{1/2} \right](3b^2P - 3bP^2 + P^3),$$

k being merely a proportionality constant.

I_m, the maximum ionization produced, is found by putting $P=b$. Hence $I_m = ka^2b^2/6(a^2+b^2)^{1/2}$,
and

$$I = I_m(3P/b - 3P^2/b^2 + P^3/b^3).$$

This equation holds, of course, only for $0 \leqq P \leqq b$. Pressures greater than b correspond to complete absorption of the ionizing radiation, and hence to a constant $I = I_m$.

In this case there is little seeking for arbitrary constants. I_m is the final maximum ionization and b is the lowest pressure at which this maximum is obtained. In curve III, for instance, $I_m = 45.43$. In this case the maximum ionization appears to occur first at about 130 atm. However, the pressure rate of increase of I at high pressures is so very small that the actual maximum range probably corresponds to a somewhat higher pressure. Taking $b = 140$ atm., the values represented by the open circles in Fig. 7 were obtained. These are rather low between 1 and 60 atm.

Arbitrarily assuming 4/5 of the final maximum ionization to be due to radiation of the above type with a maximum range corresponding to 150 atm. in the bomb, and the remaining 1/5 to be due to a similar radiation with a maximum range corresponding to 40 atm., the values represented by crosses in Fig. 7 were obtained. These fall very close to the experimental curve.

The actual situation must have been much more complicated than that postulated in the above analysis. For instance, the initial recoil electrons would not be expected to be emitted in none but radial directions, and there would probably be several consequent radiations with decreasing energy content. It is hoped that a more careful analysis with more likely assumptions may be effected in the future. However, the writer opines that these considerations show, in so far as the observed $I-P$ relation is concerned, that it is reasonable to assume the ionization to have been produced entirely by secondary radiations, perhaps recoil electrons, excited in the walls of the vessel by the primary penetrating radiation.

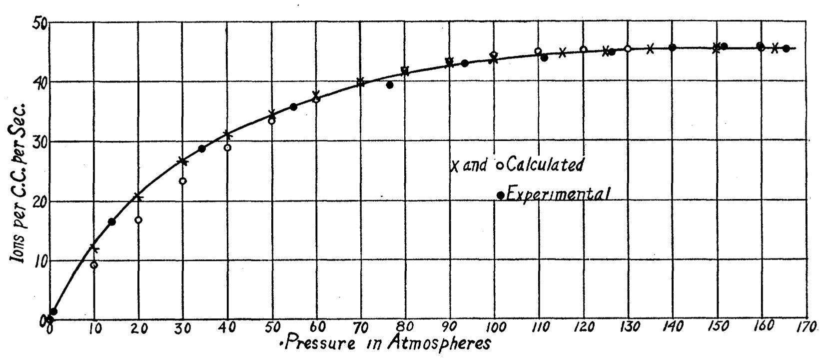

Fig. 7.

Significance of the the recoil electron assumption

If the explanation suggested above is correct and the ionizing radiation really consisted of recoil electrons, their range in the air should give some information concerning the penetrability of the primary radiation. Millikan and Cameron[10] have shown in detail how to calculate by means of Compton's[11] equations the range of the recoil electrons which would be generated by a very penetrating radiation of known coefficient of absorption. In the present instance we may proceed in precisely the reverse order.

If we consider recoil electrons of range about 140 diameters of the bomb at 18° C or 38 meters in air at N. T. P., and use the 1926 procedure of Millikan and Cameron based upon the work of Bohr and Varder, we obtain 10.94×10^6 volts for their initial energy. According to the empirical formula found by Feather[12] to hold for penetrating β-rays, the energy would be 10.09×10^6 volts. As Millikan and Cameron pointed out, at such high energies

[10] R. A. Millikan and G. H. Cameron, Phys. Rev. **28,** 851 (1926).
[11] A. H. Compton, Phys. Rev. **21,** 483 (1923).
[12] N. Feather, Phys. Rev. **35,** 1559 (1930).

the Compton theory predicts the equipartition of the energy of the incident quant between the recoil electron and the scattered quant. Thus, using the first value above, the primary radiation would have an energy-value of 21.89×10^6 electron-volts, or a wave-length of 0.00052A. Substitution of this in the Compton absorption formula gives an absorption coefficient in water of 0.0025 cm^{-1}.

The agreement of the value of μ just calculated with the experimental values is rather startling in view of the fact that the Compton theory, based upon the older quantum mechanics, is now in bad grace. Klein and Nishina[13] have calculated for the scattering coefficient, which may be regarded as the absorption coefficient for sufficiently high frequencies,

$$S = \frac{2\pi Ne^4}{m^2c^4}\left\{\frac{1+\alpha}{\alpha^2}\left[\frac{2(1+\alpha)}{1+2\alpha} - \frac{1}{\alpha}\log(1+2\alpha)\right] + \frac{1}{2\alpha}\log(1+2\alpha) - \frac{1+3\alpha}{(1+2\alpha)^2}\right\}.$$

In this formula, based on wave-mechanics, $\alpha = h\nu/mc^2$, e is the electron charge, m the electron mass, c the velocity of light, ν the frequency of the incident radiation, and N the number of "external" electrons per cc. S represents loss of energy from the incident radiation due both to the energy transferred to the scattered radiation and to the recoil electrons. It was obtained directly by multiplying the expression

$$I = I_0\frac{e^4}{2m^2c^4r^2}\,\frac{1+\cos^2\theta}{[1+\alpha(1-\cos\theta)]^3}\left\{1+\alpha^2\frac{(1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]}\right\}$$

for the intensity of the radiation scattered per electron at an angle θ, in terms of I_0, the intensity of the incident radiation, by ν/ν', the ratio of the frequencies of the incident and scattered radiations, and by $Nr^2d\Omega/I_0$, and integrating over the entire solid angle about a point. If we proceed in the same manner without multiplying by the term ν/ν', we obtain

$$S_s = \frac{2\pi Ne^4}{m^2c^4}\left[\frac{\log(1+2\alpha)}{2\alpha^3} + \frac{\alpha^2-\alpha-1}{\alpha^2(1+2\alpha)} + \frac{4\alpha^2+6\alpha+3}{3(1+2\alpha)^3}\right].$$

This represents loss of energy by virtue of the scattered radiation alone, and corresponds to N times Compton's[11] σ_s, or "true scattering coefficient" per electron.

The ratio $(S-S_s)/S = E/h\nu$, where E is the energy of the scattered electron, is the ratio of the mean energy per scattered electron to the energy of an incident quant. If we take $E = 11\times 10^6$ electron-volts, we find the last equation is approximately satisfied by $\lambda = 0.000892$A. With this value of the wave-length of the incident radiation we obtain $S = 0.020$ cm^{-1} for water, and $E/h\nu = 0.8$. Thus, according to the Klein-Nishina theory, the energy at very

[13] O. Klein and Y. Nishina, Zeits. f. Physik **52,** 853 (1929).

high frequencies is not distributed equally between the scattered quant and the recoil electron, but most of it is absorbed by the latter, the recoil electron in the present instance absorbing 4/5 of the energy of the incident quant. Using the supposedly observed range of the recoil electrons, we have calculated by the Klein-Nishina theory an absorption coefficient for the primary penetrating radiation which is one order of magnitude higher than that calculated by the Compton theory and found experimentally.

An absorption coefficient of 0.0024 cm^{-1} of water corresponds, according to the Klein-Nishina formula, to a primary wave-length of about 0.00006A. Substitution of this in the above expression for $E/h\nu$ gives 1.8×10^8 electron-volts for the energy of the recoil electrons. If we consider the range of an electron of high energy content to be proportional to its energy, the range to be expected according to this theory is about $38\times180/11=622$ meters in air at N. T. P., some 16 times that assumed to have been measured in this investigation.

The two theories of scattering agree very well in the x-ray region, but differ greatly at very much higher frequencies, as shown above. The Klein-Nishina theory has recently been found by several investigators[14] to agree much better with observations in the region of very penetrating γ-rays than does the Compton theory. This would indicate that the final, constant maximum ionizations observed in the present investigation do not correspond to complete absorption of the recoil electrons. If, on this basis, the suggested explanation in terms of some sort of secondary radiation from the walls of the vessel is considered entirely untenable, then it seems to the writer that the true explanation must depend upon some characteristics of gaseous ionization at high pressures or of absorption in that region, which are not known.

In this connection it may be mentioned that Skobelzyn[15] has observed by the Wilson cloud method paths which he considers to have been due to recoil electrons excited by the cosmic radiation, and whose energy he has estimated from the curvature of the path in a magnetic field, to have been about 15×10^6 volts at the beginning of the observed portion of the path. He points out that this value was to be expected on the basis of the older theory but is inclined to discard it in favor of the newer, and suggests the possibility of the corpuscles originating outside the expansion chamber, or of the mechanism of absorption of energy in the region of such high frequencies being of a different sort from that ordinarily postulated in Compton scattering, perhaps with the ejection of H particles from the nuclei. (Note also the suggestion of nuclear absorption in the papers of reference 14.) "In diesem Zusammenhang könnte man auch an die Möglichkeit, dass die H-Strahlen mit der Energie von dem Betrage der "Ultra-γ-Energie" erzeugt werden können, denken. Diese H-Strahlen würden die Geschwindigkeit von der Ordnung 1,5 bis 2.10^{10}

[14] C. Y. Chao, Nat. Acad. Sci. Proc. **16,** 431 (1930); Phys. Rev. **36,** 1519 (1930). G. T. P. Tarrant, Proc. Roy. Soc. **128,** 345 (1930). D. Skobelzyn, Zeits. f. Physik **65,** 773 (1930). L. Meitner u. H. H. Hupfeld, Zeits. f. Physik **67,** 147 (1931).

[15] D. Skobelzyn, Zeits. f. Physik **54,** 686 (1929).

haben." Taking the lower of the values suggested and Rutherford's[16] value of 3.07×10^9 cm/sec for the initial velocity of an H atom of range 28 cm in air, and assuming the ranges proportional to the cubes of the velocities, we have $R=0.28(15/3.07)^3=33$ meters in air, a value comparable to the range of the secondary radiation discussed in this paper. Of course, the "Ultra-γ-Energie" has been calculated on the basis of absorption measurements and the assumption of electron scattering, so that it is questionable as to what weight may be given the suggestion. If one might suppose that such positive corpuscular radiations could produce considerably more ionization than the recoil electrons in the present instance, however, there would be a possibility of using the notion in explaining the observed variation of ionization with pressure.

Possibly it is worth while pointing out that in so far as the present investigation indicates the very considerable importance of secondary radiations excited by the cosmic radiation and suggests by virtue of their relatively low penetrating power that they are corpuscular in nature, the penetrating corpuscular radiations detected by some investigators[17] may be suspected of being secondary in nature.

It would appear to be a rather conservative conclusion, on the basis of the experiments herein presented, that the ionization in a closed vessel which is properly attributable to the penetrating radiation depends to a considerable extent upon the vessel and other circumstances. Such dependence does not seem to have been taken into account, for instance, by Hulburt[18] in calculating the contribution of the cosmic penetrating radiation to the ionization of the free atmosphere at various altitudes. He takes as the value at sea-level, 1.4 ion/cc sec which was the value measured by Millikan in two different electroscopes. But in the case represented by curve II, with a 2-in. lead shield at an altitude of 5400 ft., only 52 pairs of ions were actually produced in 1 sec in a region which was occupied by a quantity of air which would occupy about 159 cc at N. T. P. Presumably, this ionization was due partially to energy absorbed from the penetrating radiation by the walls of the vessel as well as by the air itself. It would seem, then, that the ionization produced by the cosmic radiation in the atmosphere, if free from dust or other suspended particles, would be considerably less than that calculated on the basis of 1.4 ion/cc·sec at sea-level. This situation has been emphasized by Swann[19] on the basis of the earlier ionization-pressure experiments. To quote: "Thus, the actual ionization in the vessel, due to primary and secondary emission from the gas, will be less at one atmosphere than at any higher pressure. If then, the ionization-pressure curve should show a very small increase of ionization per atmosphere increase at high pressures, we know from the above that such increase per atmosphere is nevertheless greater than the portion

[16] E. Rutherford, Phil. Mag. **37**, 537 (1919).

[17] W. Bothe u. W. Kolhörster, Zeits. f. Physik **56**, 751 (1929). B. Rossi, Accad. Lincei, Atti **11**, 478 (1930). L. F. Curtiss, Phys. Rev. **34**, 1391 (1929).

[18] E. O. Hulburt, Phys. Rev. **37**, 1 (1931).

[19] W. F. G. Swann, Bull. Nat. Research Council **3**, part 2, 65 (1922).

of the ionization due to primary and secondary action in the gas within the vessel at one atmosphere. We may infer that any greater ionization found at atmospheric pressure is to be attributed to radiation from the walls of the vessel; this radiation, owing to its absorption at the higher pressures, results in a diminishing rate of increase of ionization with pressure. . . . If one were to accept this parallelism without reservation, he would be forced to conclude that the portion of the ionization within the vessel which was attributable to the direct or indirect action of the (penetrating) radiation on the gas was immeasurably small."

Naturally, if one ionization chamber is used by each observer throughout his investigations, values of the absorption coefficient of the penetrating radiation measured by different observers should agree fairly well, as they do.[8] However, the estimates of the intensity of the radiation based upon ionization measurements would be expected to differ and such agreement as exists probably depends upon the fact that no vast differences have existed among the experimental conditions. The writer is inclined to believe that differences in the effects of secondary radiations may in some instances play even a more important part than the "zeros of their instruments"[20] in explaining the lack of agreement among different experimenters as to the intensity of the primary cosmic radiation.

Dependence upon time

The question of the variation with time of the natural ionization in gases has been a matter of investigation for a good many years, with a great deal of resultant disagreement. Very recently a diurnal variation in the ionization produced by the cosmic radiation has been observed by Millikan[21] and by Hess.[22] They both agree that this ionization is somewhat greater during the day than during the night, an indication of which was formerly observed by the writer.[2]

Hess explains the variation on the basis of penetrating radiation originating in the sun, while Millikan considers it to be due to variations in atmospheric absorption, and shows a correlation with variations of atmospheric pressure. Whatever the explanation, it has probably occurred to the reader that this effect might serve to explain the constancy of the ionization observed in this investigation at the very high pressures. If the ionization at the highest pressure were observed when the intensity of the cosmic radiation happened to be at a minimum and if the ionization at successively lower pressures were measured with an increasing radiation intensity, a high-pressure slope which might have existed could the measurements at different pressures have been made simultaneously, could conceivably have been compensated. However, this was not the case. Millikan[21] found the intensity of the cosmic radiation to pass through a maximum in the late afternoon and a

[20] R. A. Millikan and G. H. Cameron, Nature **121**, 19 (1928).
[21] R. A. Millikan, Phys. Rev. **36**, 1595 (1930).
[22] V. F. Hess, Nature **127**, 10 (1931).

minimum at night or in the early morning. In the cases of curves I–IV, the observations at the highest pressures were begun in the respective instances at 5:31 P.M. Apr. 26, 4:14 P.M. May 24, 6:00 P.M. July 19, and 3:23 P.M. June 21, 1930. In the cases of curves I, II and IV the low pressure ends of the practically horizontal portions of the curves at about 130 atm., were reached at about 2:00 A.M. of the following days, and in the case of curve III, at midnight. Atmospheric pressure was usually reached by the evening of the second day.

The observed constancy of the ionization at the high pressures might therefore be considered to constitute evidence against variations of the type mentioned. This need not follow when it is considered that we have here only three instances of extreme constancy. In particular, during the period of the observations for curve II a sensitive barograph was kept in the room with the other apparatus where the temperature was very uniform, and no fluctuations of more than 1 mm occurred during the entire period. The barometric pressure was not observed in the other instances except in connection with the readings at atmospheric pressure, whence a similar constancy may have happened to exist. However, the observed constancy of ionization, in connection with the way the end points fit into the curve of Fig. 6, otherwise observed Aug. 16–17, tends to provide interest in a careful investigation of the variation with time of the ionization in the vessel at the very high pressures.

In conclusion, the writer desires to express his sincere appreciation of assistance received from several sources. Funds in aid of this research were provided by the American Association for the Advancement of Science. The Mountain States Telephone and Telegraph Co. on behalf of the Bell System provided some two tons of lead. The staffs of the several Engineering Departments of the University rendered very generous assistance; in particular, Professor S. L. Simmering and Mr. C. A. Wagner of the Department of Mechanical Engineering compressed all the air used in this investigation. Assistance in recording observations was given by Professor G. B. Williston and by Messrs. Louis Strait, J. M. Porter, Sydney Hacker and Ralph Warren. The photograph was taken by Mr. R. A. Merrill. Professor Swann has read and criticized the paper.

Fig. 1. Photograph of apparatus.