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Cosmic-Ray Ionization as a Function of Pressure, Temperature, and Dimensions of the Ionization Chamber

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Experiments have been performed to test the adequacy of the writer's explanation of the dependence upon pressure of the cosmic-ray ionization in gases at high pressures in terms of subsidiary radiations emitted solely from the walls of the ionization chamber. The ionization in a 436 cc sphere of 33.32 g mass located at the center of the 660 lb. bomb of 13.8 liters capacity used in previous experiments, was found not to differ greatly from the average ionization in the large chamber at corresponding pressures up to 175 atmospheres. At the higher pressures gamma-ray ionization and cosmic-ray ionization were found to vary with the pressure in the same manner. These facts are considered to be incompatible with the explanation mentioned above. The temperature effect was found to amount to 0.19 percent increase in ionization per centigrade degree increase in temperature at a mean pressure of 23.3 atmospheres, and 0.27 percent per degree at 162.1 atmospheres, in qualitative but not entirely in quantitative agreement with the theory and observations of Compton, Bennett and Stearns. The cosmic-ray ionization at 205 atmospheres in the shielded bomb was found to agree within about one percent with the upper limit previously observed in the same chamber with similar shielding at pressures between 130 and 170 atmospheres. Certain transient effects associated with changes in pressure and temperature were observed.

Continuing the investigation of the residual ionization in gases at high pressures, the writer found that the ionization produced by the penetrating radiation in air[1] approached an upper limit at about 130 atmospheres in a spherical chamber of 11.72 inches internal diameter. No change in the ionization was observed as the pressure was increased to 170 atmospheres. A similar situation was observed in the case of nitrogen,[2] but in this gas the ionization was greater than that in air at corresponding pressures, and constant values were obtained only at a somewhat higher pressure. Earlier work[3] had shown oxygen to resemble air, and carbon dioxide to resemble nitrogen, at pressures up to about 70 atmospheres.

Amplifying the hypothesis suggested by McLennan[4] and later by Wilson[5]

[1] J. W. Broxon, Phys. Rev. **37**, 1320 (1931).
[2] J. W. Broxon, Phys. Rev. **38**, 1704 (1931).
[3] J. W. Broxon, Phys. Rev. **27**, 542 (1926).
[4] J. C. McLennan, Phil. Mag. **14**, 760 (1907).
[5] W. Wilson, Phil. Mag. **17**, 216 (1909).

and Downey,[6] the writer showed that the relation between ionization and pressure could be explained by assuming that the penetrating radiation produced no appreciable primary ionization, the immediate ionizing agent being secondary radiations excited only in the thick walls of the container. For two reasons the explanation appeared rather unsatisfactory. In order to explain the constant value of the ionization at sufficiently high pressures, it was necessary to assume that all the subsidiary radiations were emitted in directions normal to the inner surface of the chamber. Further, it appeared unlikely that secondary radiations should not be excited in the gas at the high pressures as well as in the vessel walls, inasmuch as altitude measurements indicate that the penetrating radiation is absorbed in air as in other materials.

Compton, Bennett and Stearns,[7] and Millikan and Bowen[8] have emphasized an alternative explanation. According to them the attainment of constant ionization values at the high pressures is due to a lack of saturation. This lack of saturation is due to a selective recombination, the recombination of the ion with the parent from which the electron was ejected, rather than to random recombination. On this account, the ordinary tests for saturation are found to be inadequate.

With this point of view, Compton, Bennett and Stearns were able to deduce an equation giving the proper variation of the ionization with pressure. They were further able to deduce a dependence upon temperature, insignificant in the neighborhood of atmospheric pressure, but considerable in the neighborhood of 100 atmospheres. The temperature effect was checked experimentally by measurements of the ionization produced in air and nitrogen by gamma-rays, greater ionization currents being observed at higher temperatures.

Bowen[9] has also provided experimental evidence for the selective recombination hypothesis by showing that at pressures up to 93 atmospheres the ionization produced by gamma-rays increases with the potential gradient up to 1000 volts/cm, and that the dependence upon the gradient is nearly independent of the intensity of the ionization. This observation conflicts with the detailed theory of Compton, Bennett and Stearns, according to which a very much higher gradient would be required to increase the ionization current above the apparent saturation value.

The dependence of the ionization by gamma-rays in air and carbon dioxide upon pressure, temperature and potential gradient was carefully investigated by Professor Erikson[10] in 1908. He found that as the pressure was varied from 1 to 400 atmospheres the ionization in air actually passed through a maximum, thereafter decreasing linearly with increase of pressure. The magnitude of this maximum and the pressure at which it occurred increased

[6] K. M. Downey, Phys. Rev. **16**, 420 (1920); **20**, 186 (1922).
[7] A. H. Compton, R. D. Bennett and J. C. Stearns, Phys. Rev. **39**, 873 (1932).
[8] R. A. Millikan and I. S. Bowen, Nature **128**, 582 (1931).
[9] I. S. Bowen, Phys. Rev. **41**, 24 (1932).
[10] H. A. Erikson, Phys. Rev. **27**, 473 (1908).

with the potential gradient, the maximum gradients being provided by 2500 volts between gauze cylinders differing by 0.8 cm in radius. He found at a constant pressure that after an initial rapid increase the ionization continued to increase slightly with the potential gradient to the highest values used. At constant gas density, he found the ionization increased with temperature when high potential gradients were applied, whereas the ionization decreased with increasing temperature at low field intensities. The effects were explained by Professor Erikson in terms of the selective recombination with the parent atoms.

In addition to explaining the variation with pressure, an interesting feature of the secondary radiation hypothesis was that it led to correct values of the absorption coefficient of the primary penetrating radiation, upon assuming that the ranges of these radiations were represented by the diameter of the vessel at the lowest pressure at which the maximum ionization was attained, and the further assumption that they consisted of electrons scattered in such a manner that the Compton equation was applicable. That the application of this equation was quite unjustified was recognized, but the assumption that the secondary radiations consisted of protons ejected from the nucleus upon absorption of an incident quantum led to a similar conclusion. In this connection it is of interest that Millikan and Anderson[11] have found from expansion chamber observations in a magnetic field, that the secondary radiations are chiefly positive. Compton, Bennett and Stearns[7] provide evidence in contradiction of this phase of the explanation. They have found the ratio of the ionization by a given intensity of gamma-radiation to that produced by the cosmic penetrating radiation in the same vessel at the same pressure, to be quite independent of the pressure within the range of their measurements. If the ionization in both cases were due almost entirely to secondary radiation from the walls, then a maximum ionization should be attained at a considerably lower pressure in the case of the gamma-radiation, in view of the much lower energy of the incident quanta in this case.

Sievert[12] and Tarrant[13] have also observed a pressure effect in gamma-ray ionization corresponding to that observed by the writer with cosmic-ray ionization, and the former has obtained pressure-ionization curves with x-radiation which somewhat resemble Professor Erikson's high-pressure γ-ray ionization curves. They also consider the secondary radiation hypothesis unsatisfactory.

In an attempt to test further the adequacy of the suggested explanations of the characteristics of the ionization due to the penetrating radiation in gases at high pressures, the present investigation was undertaken.

Ionization in Thin Central Sphere

The assumption that the ionization in a gas by the cosmic penetrating radiation is due entirely to secondary radiations emitted normally from the

[11] R. A. Millikan and C. D. Anderson, Phys. Rev. **40**, 325 (1932). Also, see the conclusions of E. G. Steinke and H. Schindler, Zeits. f. Physik **75**, 115 (1932).

[12] R. M. Sievert, Nature **129**, 792 (1932).

[13] G. T. P. Tarrant, Proc. Roy. Soc. **A135**, 223 (1932).

walls, would lead to the conclusion that the ionization in the central region of a spherical chamber should vary considerably from the average. At the lower pressures the ionization should be greater at the center whereas at high pressures it should be less, becoming negligible at sufficiently high pressures.

The difficulty with ascertaining the ionization in a given region is that solid material must be introduced in order to perform the measurement, and this material modifies the conditions. To approximate the desired conditions, an exceedingly thin vessel should be introduced into the central region.

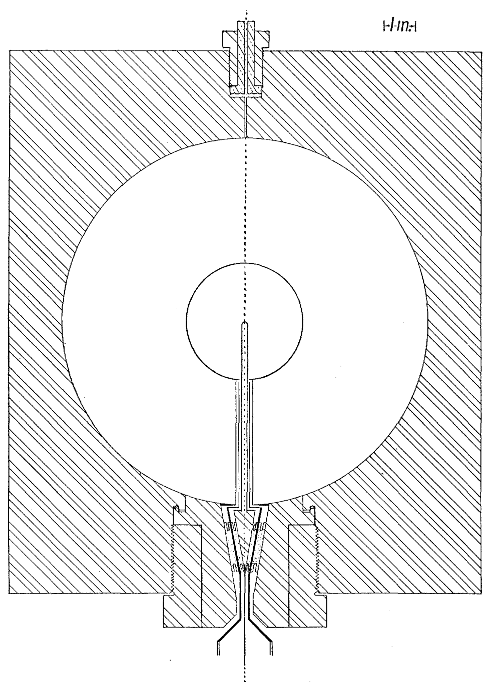

Fig. 1. Longitudinal section of ionization chamber.

Because it was highly desirable to know very definitely the region from which ions were drawn in the present instance, it was decided to construct a chamber with thin but continuous walls. Consequently, two thin steel hemispheres were spun, ground down to a still smaller thickness, and soldered together. This sphere was mounted at the center of the 11.72 in. bomb used in recent work,[1] as shown in Fig. 1.

The mass of the central sphere was 33.32 g. Its volume, as determined by filling and weighing with benzene whose density was carefully determined at the temperature of the experiment, was 436.7 cc, giving a mean internal diameter of 3.706 in. Division of the mass of the sphere by its area and the probable density of the steel gave an average wall thickness of about 0.006 in. Micrometer measurements showed the external diameter to vary between 3.712 and 3.746 in.

The large tube supporting the thin sphere had an outside diameter of 0.532 in., a wall thickness of 0.008 in., and weighed 7.40 g. The central tube, forming a continuation of the guard system, had an O.D. of 0.342 in., a wall thickness of 0.007 in., and weighed 4.09 g. The innermost tube, forming the collector, had an O.D. of 0.168 in., a wall thickness of 0.011 in., and weighed 3.90 g. The end of this tube was spun to an approximate hemisphere. The hole in the sphere through which this tube was admitted was 9/32 in. in diameter. The volume of the tube inside the sphere was 0.67 cc, leaving a free volume of 436 cc inside the sphere.

The tubes and sphere were mounted on the plug[14] of the large bomb, and when the latter was screwed into place the eccentricity of the central sphere relative to the interior of the bomb did not amount to more than 1/32 in. The tubes were beneath the sphere. Twenty small holes were drilled in the outer tube to allow an equalization of pressure inside and outside the thin sphere. None were drilled within $\frac{1}{2}$ in. of the ends of the tube, however.

Because of the very much smaller volume, the ionization currents were correspondingly smaller than in the large sphere. However, for purposes of comparison, it was considered desirable to use precisely the same measuring equipment which had been used in the preceding high-pressure work. This equipment, the location, the method of measurement, etc., have been described fully.[1] The insertion of the small sphere constituted the only alteration; the same constant, modified by the volume ratio, yielding the number of pairs of ions per cc per sec. when multiplied by the number of volts/sec. applied to the compensating condenser. Because of the smaller currents, however, six or eight 15-minute readings or three or four 30-minute readings were made at each pressure, instead of the usual three 8-minute readings. Also, positive and negative ions were usually collected during alternate readings to insure that the smaller readings would not be affected by possible contact potentials or zero drift. That no appreciable deformation of the sphere occurred during the observations was shown by the fact that its induction coefficient relative to the central system varied linearly with the pressure, a situation which had been found to hold in the case of the rigid bomb.[15]

As in all previous work, the gas used throughout the present investigation was aged at least four weeks, often much longer, and was dried and freed from dust. With the bomb surrounded by the water shield only, observations of the ionization in the central sphere were made at various pressures between about 7 and 175 atmospheres. These are shown in Fig. 2, pressures again being reduced to 18°C. The dotted curve represents the average ionization measured in the large bomb under the same conditions; it is curve III of Fig. 5 of the paper of reference 1. The small square represents an observation of the

[14] In order to eliminate a small leak, the main plug was redesigned to conform with the small one at the top of the bomb, so that the portion of the plug in contact with the gasket was not allowed to rotate as the plug was tightened. This design proved to be thoroughly satisfactory.

[15] J. W. Broxon, Phys. Rev. **37,** 1338 (1931).

ionization in the small sphere with the lead shield only, and the cross represents the ionization measured with both the lead and water shields. The barometric pressures during the two series of observations with only the water shield did not differ by more than 0.05 in. It appears that the two observations designated by the square and the cross should be reduced by about 0.6 percent to conform to this barometric pressure.

The striking thing about the curve is its proximity to the dotted curve. The ionization in the central sphere seems to be definitely higher than the average in the large bomb at the lower pressures and a little lower at the highest pressures. However, constant values at high pressures are again attained,

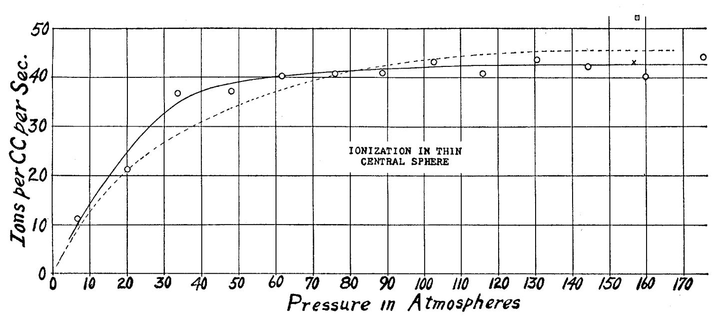

Fig. 2.

in this case at a lower pressure than in the large chamber. There are apparent differences between the curves, but not at all of the magnitude to be expected on the hypothesis of ionization due entirely to radiation from the walls. It is a striking observation that at the highest pressures the ionization in this small central sphere, weighing little more than an ounce, containing air weighing nearly three times as much, and surrounded by a blanket of air equivalent to a layer more than 50 ft. thick at atmospheric pressure, should be so nearly the same as the average ionization in the 660 pound bomb containing more than thirty times as much air.

Ionization by Gamma-Rays

In order to compare the effects of cosmic rays and gamma-rays, about 2.85 mg of radium sulphate equivalent to 2 mg of Ra in Aug., 1923, sealed and enclosed in a container (apparently with 7.5 mm lead and 1.5 mm steel walls) was placed in a cabinet about two ft. outside the water tank surrounding the bomb. The radium was thus displaced horizontally about 9 ft. from the axis of the bomb, and about 21 in. below its center. The lead and water shields were removed from about the bomb, but the gamma-rays still had to penetrate the 9 mm lead-steel container, 2.5 in. of wood, 8.5 ft. of air, and the 1.7 to 6 in. steel walls of the bomb. With this arrangement, the gamma-ray ionization produced in the 13.8 liter chamber at the high pressures was about five times as great as that produced by the cosmic radiation with lead and water shields. Although the same potential, about 875 volts, which has been impressed across the ionization chamber throughout these investigations was still used, it was perhaps not sufficient to produce saturation. At the highest pressure employed a decrease of 29 percent in the impressed voltage produced a decrease of about 1 percent in the ionization current.

The gamma-ray ionization is shown plotted against the pressure in Fig. 3. The values shown are not those actually observed. From the observed values were subtracted the residual ionization observed at corresponding pressures with no shields, curve I, Fig. 5, of the paper of reference 1. The differences,

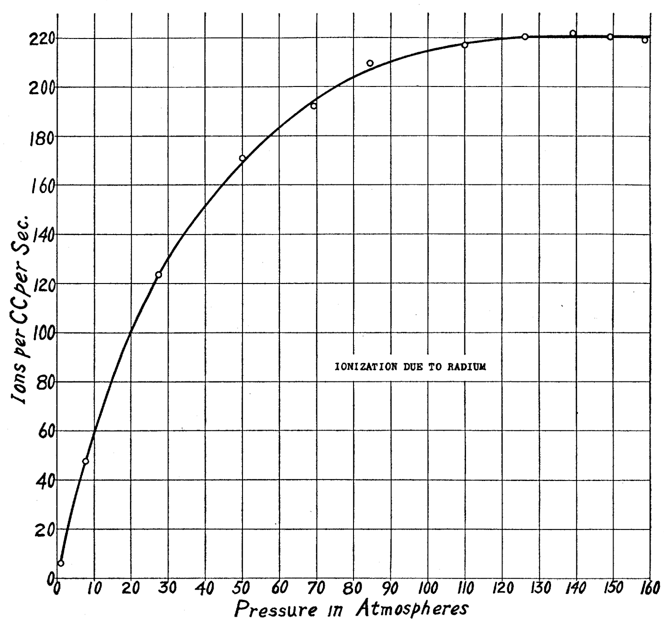

Fig. 3.

considered to represent the ionization actually produced by the gamma-radiation, are shown in Fig. 3.

The ratios of the gamma-ray ionization I_R to the cosmic-ray ionization I_C at corresponding pressures are shown in Table I. The cosmic-ray ionization values considered in this table are those obtained with both lead and water shields, represented by curve IV, Fig. 5, of the paper of reference 1. It is seen that the ratio is not quite constant, although it is nearly so at pressures above 60 atmospheres. This is not in full agreement with the observations of Comp-

TABLE I.

Atm. press.	0.82	10	20	30	40	50	60	70	80	90
I_R/I_C	4.21	4.90	4.97	5.07	5.07	5.13	5.17	5.20	5.20	5.17
Atm. press.	100	110	120	130	140	150	160			
I_R/I_C	5.16	5.16	5.17	5.17	5.18	5.18	5.18			

[16] J. C. Stearns and W. Overback, Phys. Rev. **40,** 636 (1932).

ton, Bennett and Stearns.[7] Stearns and Overback[16] have recently found the ratio to be constant for pressures between 5 and 70 atmospheres. The smaller ratios at low pressures in the present instance might possibly be explained in terms of a very minute contamination of the vessel with decreasing effectiveness at higher pressures, of the type described by Millikan.[17] That such a contamination must necessarily be very small has been shown by the experiments with different shields at high and low pressures.[1] In any case, however, it is seen that the agreement between the gamma- and cosmic-ray ionization-pressure curves is entirely too good to permit of the explanation solely in terms of secondary radiations from the walls, in view of the conclusion that the ranges of these radiations should increase with the penetrability of the incident radiation.

Temperature Effect

To vary the temperature of the bomb, steam was passed from the University heating plant into the water surrounding the bomb and circulation was provided by a centrifugal pump which withdrew water from the bottom of the tank and returned it at the top. The lead shield was not used during

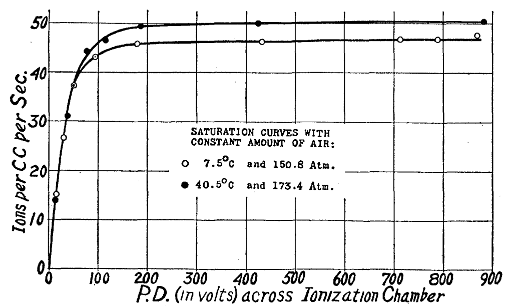

Fig. 4.

the temperature measurements. The water level was maintained constant during the temperature changes, this level being about $\frac{5}{8}$ in. lower than the top of the tank whereas previous experiments with the water shield were all made with the tank full. The steam was available only at a low pressure. In view of this fact it is apparent that changes in the temperature of the 660 lb. steel bomb, surrounded by an air space about 3 to 4.5 in. thick and then by more than 15,000 gallons of water, could be produced only very slowly.

Cold water was first passed rapidly into the tank through fire hoses. About 24 hours later ionization measurements were begun. In order to demonstrate the degree of saturation, observations were made with different applied potentials. The relation between the ionization and the potential drop across the ionization chamber, itself, is shown by the lower curve of Fig. 4. During these observations the average temperature of the bomb was 7.5°C, the average pressure of the gas was 150.8 atmospheres, and the barometric pressure, 24.55 in. The value of the ionization was considered to be

[17] R. A. Millikan, Phys. Rev. **39**, 397 (1932).

46.8 ions per cc per sec. The high potential observations were made first, and during the 10.5-hour period of the observations the temperature was decreasing at the rate of about 0.05°C per hour.

Steam was next passed into the water for several days. The steam was then shut off and another series of observations similar to those at the low temperature were made. During this period the average temperature was 40.5°C, the average pressure 173.4 atmospheres, and the barometric pressure, 24.87 in. The ionization under these conditions was considered to be 50.1 ions/cc sec. The temperature was again decreasing at the rate of about 0.05°C per hour. The ionization-potential relation under these conditions is shown by the upper curve of Fig. 4.

The air used during these observations was retained in the chamber at constant density for about a month, during which period a 15-day series of observations relative to the diurnal variation[18] were made, the same air being used later for the γ-ray measurements described earlier in this paper. During this time no leak was observed. During the 15-day series of observations, the average ionization was 47.25 ions/cc sec., the average temperature, 17.42°C, and the average barometric pressure, 24.73 in.

After measurements at 205 atmospheres to be described later, the air was released to about 22.2 atmospheres. The ionization at this pressure is designated by the lower curve of Fig. 6. After apparent equilibrium had been attained the ionization was found to be 23.43 ions/cc sec. at a pressure of 22.2 atmospheres and a temperature of 14.45°C, the barometric pressure being 24.87 in. During these observations the temperature of the bomb was increasing at the rate of 0.12°C per hour.

Later the same air was heated in the manner described above. At an average temperature of 47.25°C and a pressure of 24.3 atmospheres, with the temperature decreasing at the rate of 0.13°C per hour, the average of 12 ionization readings was 25.48 ions/cc sec., the barometric pressure being 24.43 in. The dependence of the ionization upon impressed P.D. was not investigated at the lower pressures, the maximum P.D. employed at the high pressures being used as usual. It should be mentioned that all pressures given are pressures read directly from the gauge, plus the atmospheric pressure.

It is seen that at a mean pressure of 162.1 atmospheres, changing the temperature from 7.5°C to 40.5°C resulted in an increase of the ionization amounting to about 7 percent of the lower value. At a mean pressure of 23.3 atmospheres, changing the temperature from 14.45°C to 47.25°C resulted in an increase of 8.7 percent. These are the values given in a recent note.[19] As stated there, these values had not been corrected for effects of variations in the density of the water shield with temperature, or for the effects of variations in barometric pressure. It appears that the alteration of the ionization due to change in the shielding provided by the water would amount to considerably less than 1 percent and may be neglected. A correction for barometric pressure appears to be necessary, however. When the 15-day series of

[18] The results of this investigation will be presented in an early publication.
[19] J. W. Broxon, Phys. Rev. **40**, 1022 (1932).

observations was considered, it was found that an increase of about 0.187 in. in the barometric pressure appeared to result in a decrease of 1 percent in the ionization.

The variation of the ionization with barometric pressure as designated above was somewhat larger than had been expected. Moreover, it was found that an error had been made in recording the barometric pressure during the high pressure observations. When the readings are reduced to the average barometric pressure during the 15-day series, it is found that the variation with temperature at the high pressures is greater than that at the low pressures. Thus when the barometric correction is made, the temperature effect at 23.3 atmospheres amounts to 6.2 percent for 32.8°C change in temperature, or 0.19 percent per degree. At 162.1 atm. the increase is 8.9 percent for an increase of 33.0°C, or 0.27 percent per degree. When the three ionization values, measured at constant density but different temperatures at the high pressures, are plotted against the temperature, the ionization appears to increase slightly more rapidly with increase of temperature at the higher temperatures. With such a limited number of observations, however, this observation is probably of little consequence.

The temperature effect measured at the higher pressures is seen to agree rather well with that predicted by Compton, Bennett and Stearns.[7] That observed at 23.3 atmospheres, however is considerably larger than that predicted by them, although the variation with pressure is in the right sense. The disagreement with their experimental observation with γ-ray ionization in nitrogen at 20 atmospheres is decided. The effect at 23.3 atmospheres is in good agreement with the 0.14 percent per centigrade degree observed by Wolff[20] for the γ-ray ionization in nitrogen at 21.5 atmospheres, however.

Transient Effects

As mentioned in a former paper,[1] "If measurements were made immediately after filling, larger values were obtained than after the establishment of equilibrium conditions. Therefore, from two to six hours were allowed to elapse after filling the chamber before measurements of the ionization were begun." In view of the observed temperature effect, it was thought that the high values immediately after filling the ionization chamber might be explained by the very considerable increase of the temperature of the air upon compression. The effect is shown clearly by Fig. 5, representing the first complete set of observations made with the present apparatus March 29 and 30, 1930, with no shields. In Fig. 5 as in Fig. 6, the circles represent individual observations instead of the usual average of three or four observations. The curve shown in Fig. 5 is not drawn with reference to the observations therein designated. It is curve I of Fig. 5 of the paper of reference 1, obtained under the same conditions but with a new supply of air on April 26 and 27, 1930, time for equilibrium conditions being allowed in the latter case.

The values observed very soon after filling are seen to be nearly twice as great as the equilibrium value. Increase of temperature of the bomb showed

[20] K. Wolff, Zeits. f. Physik **75**, 570 (1932).

the gas might have been heated some fifty degrees above the final temperature when compressed into the bomb. However, the temperature chart showed that the bomb had acquired a practically constant temperature before measurements were begun. Any change of temperature of the gas during the observations must have been rather small, although its temperature was probably still decreasing slightly.

In order to determine more carefully the relation between the ionization values and the time after filling, the bomb was filled with air to a pressure a

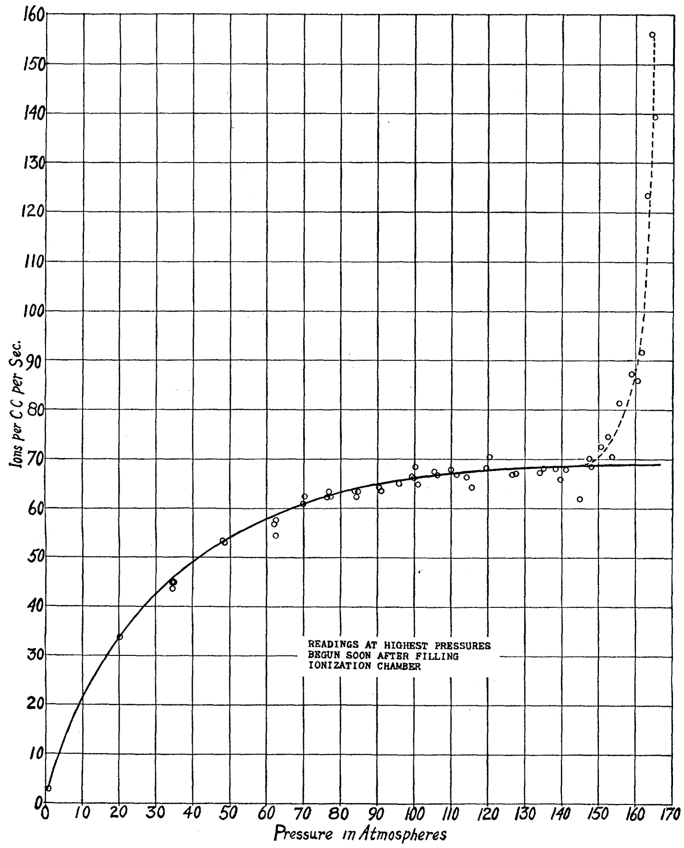

Fig. 5.

little above 205 atmospheres. The water shield with its surface $\frac{5}{8}$ in. below the top of the tank was used in this instance. The limit of the calibrated gauge used heretofore being 2500 lbs. per sq. in., the higher pressures were read on a second gauge which agreed with the first at pressures near its upper limit. After filling, the high potential was applied for a 15-minute interval before observations were begun. This has been the usual procedure. Single observations plotted against the time after filling the chamber are shown in the upper curve of Fig. 6.

The values obtained were again high at first, although as in the earlier case the bomb appeared to have acquired an equilibrium temperature before readings were begun. That the effect was not an ordinary electrical one is indicated by the fact that when the air is allowed to remain in the bomb for several hours or even days, no initial high values are observed when readings are begun, the preliminary 15-minute application of the potential always being made, of course.

The lower curve of Fig. 6 represents the ionization as a function of the time after releasing the air rapidly from about 169 to about 22 atmospheres. The potential was applied almost constantly while the air was being released, so that observations could be begun very soon after closing the valve. A slight increase was again observed, but much smaller than that following compression. A brief reference to disturbances accompanying variations in pressure has been made by Steinke and Schindler.[21]

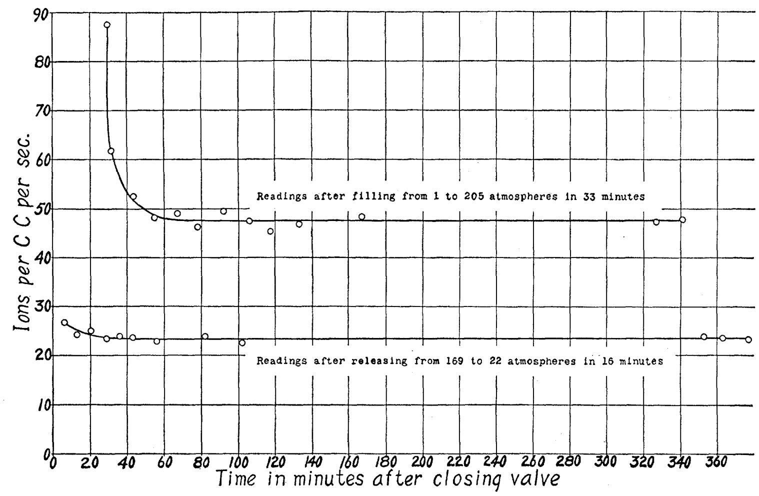

Fig. 6.

Another transient effect of some interest was observed during the temperature variations. Although changes in temperature were necessarily quite slow, the ionization at a particular density and temperature appeared to depend somewhat upon the rate of change of temperature. When the temperature was falling lower values were observed than when it was rising, so that during the investigation of the temperature effect the final steady values at a given temperature were anticipated somewhat.

The natural supposition is that these transient effects may at least to some extent be explained in terms of the characteristics of the measuring equipment. In view of the elaborate guard system and the null method employed, however, the explanation does not appear obvious to the writer.

Occasional sudden increases in the ionization current during a reading have been observed. These are quite infrequent and appear always to be well defined. Such readings have been discarded. It has been suggested that these

[21] E. G. Steinke and H. Schindler, Naturwiss. 20, 15 (1932).

sudden increases might be due to nuclear disintegration in the gas by the cosmic rays. This possibility will receive attention in future work.

Constancy of Ionization at High Pressures

After making the observations at 205 atmospheres, the air was released to 172 atmospheres. When corrected for barometric pressure, the ionization values at these two pressures were found to be nearly identical. When further corrected for the slight difference in shielding, these observations at 205 and 172 atmospheres, made in May, 1932, are only about one percent greater than the values measured with the water shield in July, 1930, at pressures between 130 and 165 atmospheres. If one may assume that there is no variation with time, the variation of cosmic-ray ionization with pressure between 130 and 205 atmospheres may be considered to be only about one percent.

Saturation

The degree of saturation attained is shown quite well in the curves of Fig. 4. Made with constant gas quantity, they represent the dependence of the current upon the applied P.D. at the pressures and temperatures shown.

Very nearly constant values appear to have been obtained in both cases. However, there is a possible increase in the ionization of one percent at the high potential end of the curves, due to doubling the applied P.D. Saturation appears much more nearly complete than in the curves of Professor Erikson's[10] experiments with γ-rays at corresponding pressures, although he used much more intense fields. Of course, the ionization he employed was vastly more intense, but if all free ions were drawn out before recombination and the lack of saturation at the high gradients was entirely attributable to (initial) recombination with the parent atoms, one should expect the degree of saturation to be independent of ion density, as Bowen[9] points out.

Bowen found that reducing the γ-ray ionization by a factor of about five at a pressure of 93 atmospheres produced very little change in the variation of the ionization current with potential gradient except at the lower gradients. It is rather surprising that the residual ionization, further reduced by a factor of about four, more nearly resembles the intense than it does the weaker γ-ray ionization in its dependence upon the gradient at that pressure, even at the lower gradients. It is these residual ionization currents which are more nearly comparable to those discussed in this paper. Throughout the range of gradients he investigated, Bowen found that at 93 atmospheres an increase of the gradient by a factor of about four produced an increase in the residual ionization current of from nearly 6 to a little more than 12 percent. This is possibly in conflict with the fact that in the present investigation the ionization in the small sphere was slightly less than that in the large one at 93 atmospheres (see Fig. 2). Since the central rods were of nearly the same size in the two cases, reduction of the radius of the surrounding vessel by a factor of more than three with the same applied P.D. of about 875 volts, should have increased the average gradient in the region of weak fields, in the neighborhood of the outer wall, by a factor probably greater than the radius ratio, although the increase of the volume average may have been small. According to Bowen's observations, then, one might expect that an appreciably greater ionization should have been measured in the small sphere than in the large one at 93 atmospheres.

Conclusions

The experiments herein described constitute further evidence in favor of the contention that the explanation of the characteristics of cosmic-ray ionization at high pressures, entirely in terms of secondary radiations from the vessel walls, is quite inadequate. The experiments with the thin central sphere and with gamma-rays can not be reconciled with that explanation.

As has been mentioned, Bowen's[9] observations of the dependence of the ionization upon potential gradient are in conflict with the details of the initial or selective recombination theory of Compton, Bennett and Stearns.[7] The curves of Fig. 4 and the observations with the small sphere appear to agree rather better with their conclusions than with those of Bowen, although a small final slope persists in the "saturation" curves. The considerable temperature effect at 23.3 atmospheres is not in quantitative agreement with their conclusions, however.

In spite of the remarkable agreement between the ionization curves of Fig. 2, the excess of ionization in the small thin central sphere over that in the large bomb in the region from 30 to 50 atmospheres appears too great to be due to experimental error. This difference might be explained in terms of secondary radiations[22] from the walls.

If, in view of the observed similarities in the characteristics of cosmic- and gamma-ray ionization at high pressures we may consider Professor Erikson's[10] observations comparable with these, the ionization should have passed through a maximum within the pressure range of the present experiments. The constant values in the present instance appear to extend over a region of at least 75 atmospheres. No maxima of such breadth were observed by Professor Erikson. Also, the equation deduced by Compton, Bennett and Stearns to approximate the writer's experimental observations indicates that an increase of 2.8 percent should accompany an increase in pressure from 130 to 205 atmospheres, whereas no increase amounting to half this much was observed. The difference is too small to be conclusive, however.

One common characteristic of both the explanations of the pressure effect is their emphasis of the importance of ionization by secondary radiations. A primary electron or proton ejected by incident cosmic radiation could scarcely be expected to recombine with its parent atom. In view of the fact that the ionization is supposed to occur chiefly through the agency of subsidiary radiations, it seems to the writer that there is another possibility deserving of some consideration. Studies of the ionization produced by alpha-rays in different gases and of the ionization potentials of these gases have shown[23] that "for the diatomic gases examined, *viz.*, H_2, N_2, O_2, the difference

[22] H. Geiger, Nature **127,** 785 (1931); H. Schindler, Zeits. f. Physik **72,** 625 (1931).

[23] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances,* p. 81. R. W. Gurney, Proc. Roy. Soc. **A107,** 332 (1925).

between the energy spent and the minimum energy required to ionise the atom . . . is very marked. In fact only about half the energy spent is required to ionise the atom. This would indicate that a considerable part of the energy of the α-particle is used up in processes which do not involve ionisation, i.e., in excitation or dissociation of the molecules." The differences are found to be much smaller in the case of the monatomic gases, particularly helium.

If this explanation is correct, it seems that a considerable portion of the gamma- and cosmic-ray energies, through the agency of subsidiary radiations, might eventually be used otherwise than in the formation of ions. Should a portion of the energy finally be dissipated in some manner such as that suggested above, such molecular processes and consequently the efficiency of ionization might be expected to depend to a considerable extent upon temperature and pressure. If such a point of view is tenable, one might expect the effects to be less in the monatomic gases.

If, as Compton, Bennett and Stearns[7] maintain, the differences between the values of the ionization measured in nitrogen and in air may be explained in terms of the selective or initial recombination hypothesis, then it should follow that complete saturation is very difficult to obtain even at atmospheric pressure. The writer has shown that the greater ionization in nitrogen persists even to atmospheric pressure.[2] In view of this and the considerable temperature effect in the neighborhood of 20 atmospheres, it seems that a careful scrutiny of ionization processes in different gases with especial regard to molecular structure should be of value. Further work of this nature is being carried on.

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