Ionization of Air by γ-Rays as a Function of Pressure and Collecting Field

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The ionization of air by γ-rays was studied for pressures from 1 to 93 atmospheres and for collecting fields from 1.55 to 1009 volts per cm. Increases in ionization current of over 40 percent were observed when the potential gradient was varied over this range, thus indicating that the lack of proportionality of ionization current with pressure obtained by previous observers was principally due to lack of saturation.

I. Introduction

THE ionization of air by γ-rays or by cosmic rays has been studied through a wide range of air pressures by Downey,[1] Fruth,[2] Broxton,[3] Swann,[4] and Millikan.[5] All of these observers agree in finding that as high pressures are reached the ionization per atmosphere decreases to a small fraction of its value at one atmosphere. In fact, the total ionization does not increase appreciably as the pressure is pushed above 100 atmospheres.

An explanation of this decrease has been proposed by Downey and elaborated by Broxton as follows. Practically all of the ionization in a gas is caused, not by the γ-rays or the cosmic rays themselves, but by the secondary β-rays ejected by them. At atmospheric pressure in any vessel of ordinary size the β-rays traversing the chamber are formed largely in the walls of the vessel. As the pressure is increased, however, the ranges of these β-particles decrease until they finally become less than the dimensions of the chamber. When this condition is reached the β-rays from the walls have produced all of the ions that they are capable of, and therefore any further increase of pressure cannot increase the total ionization caused by them. This theory appears then to predict the ionization pressure curves obtained by all observers.

However, it is a well established fact that the mass absorption coefficients of γ-rays and cosmic rays are not widely different for light substances such as air or water from their values for the metals out of which ionization chambers are usually made. Since the γ-rays or cosmic rays are absorbed in the air and since the only way in which their energy can be absorbed is by transfering it to secondary β-rays, it is obvious that the air must have approximately the same efficiency of production of β-rays as the walls. This being the case, any β-rays from the wall that are absorbed by the air are replaced by a corresponding number of β-rays ejected from the air itself. If

[1] K. M. Downey, Phys. Rev. **16**, 420 (1920); **20**, 186 (1922).
[2] H. F. Fruth, Phys. Rev. **22**, 109 (1923).
[3] J. W. Broxton, Phys. Rev. **27**, 542 (1926); **28**, 1071 (1926); **37**, 1320 (1931).
[4] W. F. G. Swann, J. Frank. Inst. **209**, 151 (1930).
[5] R. A. Millikan, Phys. Rev. **39**, 397 (1932).

this is true, the number of ions formed should be directly proportional to the pressure.

In order to reconcile this conclusion with the failure of all observers to collect this large a number of ions at the higher pressures, one is at once led to the suggestion, made independently by Millikan and Bowen[6] and by Compton, Bennett and Sterns,[7] that saturation was not attained at these high pressures, in spite of the fact that all experimenters tested for saturation in the usual way.

In all of these experiments the ionization chamber was a cylinder or sphere with a small collecting rod or fibre in the center. With this arrangement most of the potential drop is near the collecting rod while the great bulk of the chamber is subject to a potential gradient that, expressed in volts per cm, numerically amounts to only a very few percent of the total collecting potential applied. For this reason the highest potentials that these observers found it feasible to use, gave a gradient only a little above the point at which the ionization current became even approximately constant as the gradient was varied. Thus Broxton, in testing for saturation, varied his potential gradient through only 20 percent while the other experimenters carried their tests to only two or three times the gradient where the current became approximately constant. Obviously these tests would not bring to light variations of the type found in the experiments described in this paper.

II. Description of Apparatus

As no indication of a lack of saturation was found by previous observers when the collecting potential was varied through a small range, it was necessary to build an ionization chamber in which very much higher potential gradients could be applied if a satisfactory test of this lack of saturation was to be obtained. Obviously the older type of chamber was unsuited to this because of the very high total potentials necessary. Consequently a chamber was constructed in which the ions were collected between parallel plates, thus making possible a high uniform field. The ionization chamber was a steel cylinder 12.5 cm in diameter and 20 cm in length, designed to hold a pressure of 100 atmospheres. In this were placed 8 plates 10 cm in diameter which could be connected to a source of high potential. Alternating with these were 7 collecting plates 7.5 cm in diameter. These collecting plates were surrounded by grounded guard rings from which they were insulated by small amber lugs in grounded metal shields. The inside diameter of the guard rings were 7.7 cm and the outside 10 cm. The collecting plates were separated from the potential plates by 1 cm. This arrangement made possible the collection of ions from a definite known volume in which there was a uniform potential gradient which was numerically equal to the potential applied to the potential plates.

Ideally it should have been possible to measure directly the ionization by

[6] R. A. Millikan and I. S. Bowen, Nature **128**, 582 (Oct. 3, 1931), See also reference 5.

[7] A. H. Compton, R. D. Bennett and J. C. Sterns, Phys. Rev. **38**, 1565 (Oct. 15, 1931) and Phys. Rev. **39**, 873 (1932).

connecting an electrometer to the collecting plates and observing their rate of change of potential with time. Unfortunately however a change in potential of the high potential plates due to the unavoidable variation in the battery used to maintain it, produces by induction a change in potential of the collecting plates. Thus because of the large electrical capacity of the system, the ionization at the lowest pressure used, caused a change of only 0.3 volt per hour in the potential of the collecting plate. It was obviously impossible to maintain a 1000 volt battery so constant that its variation would not be an appreciable fraction of this. To compensate for this variation a second set of plates was built. This was an exact duplicate of the first set except that it was enclosed in a light brass case. The high potential plates of the ionization chamber A and the compensating chamber B were then connected to the same battery as shown in Fig. 1, while the electrometer E was arranged to measure

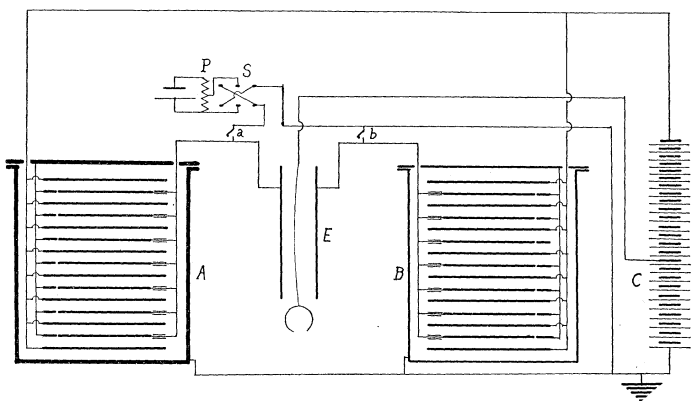

Fig. 1. Diagram of connections.

the difference in potential of the two sets of collecting plates. The electrometer used was of the single string type. The two plates of the electrometer were connected respectively to the two sets of collecting plates, while a potential of 225 volts was applied to the string. The electrometer was adjusted for a sensitivity of about 500 divisions per volt.

Because of the fact that cosmic rays at sea level cause less than $\frac{1}{4}$ of the ionization in a closed vessel, the remainder being due to γ-rays from radioactive materials in the neighborhood, and to α-rays from radioactive impurities in the walls of the ionization chamber, it was clear that more interpretable results could be obtained if the ionization of a single source such as γ-rays were studied.

For this purpose γ-rays from a small quantity of radio-thorium, filtered through 13 mm of lead were used. In order to obtain a well defined beam of γ-rays the radio-thorium and filter were placed in the center of a lead cylinder 30 cm in diameter and 30 cm long. There was a conical opening leading to one end of the cylinder which allowed a beam to pass that was somewhat larger than the ionization chamber at its position about 2 meters away. The block of lead was on a swivel so that the beam of γ-rays could be directed

either at the ionization chamber or turned to one side of it. By taking readings with the γ-rays passing through the chamber and then again with it turned to one side it was possible to determine the ionization of the γ-rays independent of the ionization of cosmic rays or α-rays.

The usual procedure in taking readings was to connect the collecting plates of the compensating chamber B to ground while the collecting plates of the ionization chamber A were held at some potential, usually 0.05 volts below ground, by means of the potentiometer P. The electrometer was then read. Next the connections a and b were broken, thus leaving both sets of collecting plates floating. The electrometer was then immediately read again, and the stop watch simultaneously started. After approximately enough time had elapsed for the collecting plates of the ionization chamber to receive enough ions to bring their potential to the same amount above that of the collecting plates of the compensating cylinder as they had started below, the electrometer position was again noted and the stop watch read. Switches a and b were now closed and this same potential above ground was then applied to the plates by means of the reversing switch S and the electrometer again read. In this way it was possible to correct for any zero drift or change in sensitivity of the electrometer.

This gave then with a considerable accuracy the rate of change of potential difference between the collecting plates. The relationship between this rate of change of potential and the ionization per cc per sec. was obtained as follows: Let C_1 be the electrical capacity between the collecting plates and the high potential plates of the ionization chamber, C_2 the capacity to ground of the collecting plates, leads and electrometer plates. By symmetry these capacities are the same for compensating chamber. Let C_3 be the capacity between the plates of the electrometer. It is then easy to show that if a charge Q is accumulated on the collecting plates of the ionization chamber and Q_2 on these plates of the compensating chamber the potential difference in volts across the electrometer is W where

$$W = (300(Q_1 - Q_2))/(C_1 + C_2 + 2C_3). \tag{1}$$

Likewise it may be shown that if the potential plates of the compensating cylinder are grounded while the potential of these plates in the ionization chamber are varied by an amount v, then the charges induced on the collecting plates (left floating) are such as to change the potential between the collecting plates of the two cylinders by an amount w, where

$$w = vC_1/(C_1 + C_2 + 2C_3). \tag{2}$$

w is obviously the change in reading of the electrometer when this variation takes place and hence can be determined directly.

From (1) it is seen that the difference of the ionization currents in the two chambers is

$$\frac{dQ_1}{dt} - \frac{dQ_2}{dt} = \frac{dW}{dt} \cdot \frac{C_1 + C_2 + 2C_3}{300} \tag{3}$$

where dW/dt is the rate of change of potential across the electrometer, in volts per sec. But substituting from (2)

$$\frac{dQ_1}{dt} - \frac{dQ_2}{dt} = \frac{dW}{dt} \cdot \frac{vC_1}{300w} \cdot \tag{4}$$

Since, however, the distance between the potential and collecting plates is 1 cm

$$C_1 = A/4\pi$$

where A is the total effective area of the collecting plates in each cylinder

$$\frac{dQ_1}{dt} - \frac{dQ_2}{dt} = \frac{dW}{dt} \cdot \frac{v}{300w} \cdot \frac{A}{4\pi} \cdot$$

The difference in the number of ions $(N_1 - N_2)$ collected per cc per sec. in the two chambers is then, since the volume from which ions are obtained is A cc and the charge on each ion is e,

$$N_1 - N_2 = \frac{1}{eA}\left(\frac{dQ_1}{dt} - \frac{dQ_2}{dt}\right) = \frac{dW}{dt} \frac{v}{w300 \times 4\pi e} \cdot$$

By taking the difference of the readings with and without the γ-rays, the N_2 cancels out and the number produced by the γ-rays alone are obtained.

Since in these experiments γ-rays giving an ionization current about 20 times as large as the natural ionization current caused by cosmic rays, α-rays etc. were used, it was advisable to test whether the form of the ionization-voltage curves was dependent on the intensity of the radiation. For this purpose determinations of the ionization currents were made, at the two highest pressures, when the γ-rays were cut down to less than $\frac{1}{5}$ of their normal intensity by being passed through 5 cm of steel.

The pressures up to 25 atmospheres were measured on a pressure gauge that was calibrated, during the course of the experiments, against a gauge tester. Consequently these values should be in error by less than 0.1 atmosphere. It was not feasible to calibrate the gauge used on the highest pressure and therefore there may be a rather large error in this pressure.

In all cases a given collecting potential was maintained on the collecting plates for several hours before readings were started to allow any charges accumulated on the insulators to take up a steady value.

III. Results

The ionization currents observed in these experiments for a series of pressures and potential gradients are given in Table I. The ionization current is expressed as the number of ions per cc per sec. per atmosphere. For the two highest pressures two columns of values are given. The first column marked I_1 represents the ionization at the full intensity of the γ-rays, that is, the same intensity as that used for the lower pressures. The second column marked 5.187 I_2 is 5.187 times the number of ions obtained when the intensity of the γ-rays was reduced by passage through 5 cm of iron. Except for the two lowest gradients at the 93 atmospheres pressure, the two columns agree within the experimental error, thus indicating that with these two exceptions

TABLE I. *γ-rays. Number of ions collected per cc per second per atmosphere.*

Field in volts per cm \ Pressure in atm.	0.98	3.74	10.50	24.95 I_1	24.95 $5.187\,I_2$	93. I_1	93. $5.187\,I_2$
1.55	112.5	101.6	79.8	59.8	59.8	26.2	28.4
6.2	118.4	106.9	86.2	63.9	63.7	29.7	30.3
23.0	118.7	110.1	89.5	66.5	66.5	30.6	30.5
91.5	120.0	113.9	94.5	70.2	70.4	32.1	31.9
367.	119.7	116.8	102.1	77.1	77.3	34.8	35.0
1009.	121.1	118.1	108.4	85.5	85.8	39.1	39.1

the form of the curves is independent of the intensity for intensities up to those used.

Fig. 2 displays graphically these data, the number of ions per cc per sec. per atmosphere being plotted against the log of the potential gradient of the collecting field P. It is at once seen that, in agreement with previous observers, the ionization per atmosphere falls off rapidly at the high pressures. Furthermore it agrees with their observation that when the potential gradient is of the order of 5 or 10 volts per cm, doubling this gradient produces a very small change in the current.

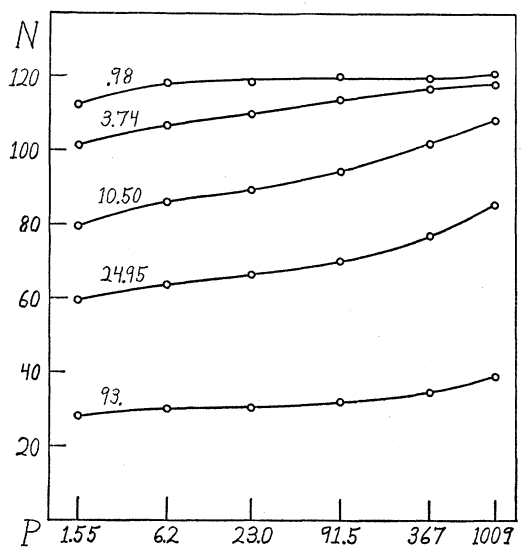

Fig. 2. The number of ions per cc per sec. per atmosphere (N) collected as a function of the potential gradient in volts per cm P for the pressures in atmospheres indicated.

However when high potential gradients are applied a very material increase of the currents is obtained thus showing that the lower gradients do not collect all of the ions formed. Thus if we assume that the number of ions per atmosphere actually formed is constant and has the value 121.1 ions per cc per sec., then the number that one fails to collect at a gradient of 6.2 volts per cm (approximately the field used by previous observers) is $(121.1 - N_{6.2})$. The fraction of these that one still fails to collect at some other higher poten-

tial P is $R=(121.1-N_P)/(121.1-N_{6.2})$. This fraction then may be taken as a measure of the success attained in pushing towards saturation by using higher fields. This fraction R as calculated from Table I is plotted against the log of P in Fig. 3.

From the figure it is seen that at 3.74 atmospheres it is possible by increasing the gradient from 6.2 to 1009 volts per cm to collect all but 21 percent of the ions that are not obtained with the lower gradient. At the higher pressures the increase of the field strength is progressively less effective.

These results provide conclusive evidence that the falling off of ionization per atmosphere at higher pressures is largely due to lack of saturation rather than to the mechanism suggested by Broxton.[8]

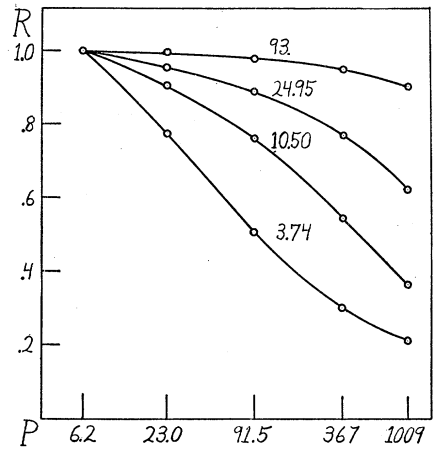

Fig. 3. $R=(121.1-N_P)/(121.1-N_{6.2})$ as a function of the potential gradient P for the pressures indicated.

Furthermore the lack of dependence of the form of the curves on the intensity of ionization, in nearly all cases, indicates that the lack of saturation is caused by recombination of the ejected electron with the parent ion rather than by random recombination between any ions formed. Presumably at the high pressures the ejected electron loses its energy before it succeeds in escaping from the region where the field of the parent ion is still very strong. This fortunately also means that this lack of saturation does not invalidate the results of many cosmic ray observers who have used high pressures, since the lack of saturation merely cuts down all currents by a constant factor and in no way effects the relative values on which absorption coefficients are based.

This increase of ionization current with potential gradient also seems to call for a modification of the theory developed by Compton, Bennett and Sterns[7] to explain this lack of saturation. According to their theory there is a

[8] There may still be a slight variation of the type suggested by Broxton due to a small difference in efficiency of production of β-rays by the air and by the steel walls of the chamber. Unpublished studies on the effect of wall materials by Workman in this laboratory indicate however that this effect of these materials is at most 30 percent and is probably in the opposite direction, i.e., it should cause the ionization per atmosphere to increase slightly with pressure.

certain critical sphere of definite radius surrounding each ion. If an oppositely charged ion finds itself inside of this sphere the force of attraction over balances the tendency to diffuse away and the two ions always recombine. On the other hand the tendency to diffuse away predominates for an ion outside of this sphere and the ion always escapes. Since at the surface of this critical sphere the field due to the ion at the center is 40,000 volts per cm any ordinary collecting field should have no effect. The question whether recombination with the parent ion takes place or not is determined, according to this theory, solely by the distance from the parent ion that the electron is ejected by the β-particle, and the factors that enter into the tendency to diffuse away such as the temperature.

Obviously this picture is much too simplified. Thus given two ions in a gas there is always a certain probability that one will diffuse close enough to the other, regardless of their original distance apart, so that recombination takes place. Of course this probability falls off rapidly as the distance increases. Furthermore this probability, particularly for an ion at a considerable distance from the parent ion, is materially changed as the strength of an external collecting field is varied. This of course changes the number that succeed in escaping from the parent ion and therefore one would expect variation in the strength of the ionization current similar to that shown in the Table I and Fig. 2.

Qualitatively this is also in agreement with the behavior indicated in Fig. 3. At the lower pressures all of the ions start at a great distance from the parent ion where its field is small and consequently the probability of recombination should be largely effected by the size of the external field, as it is found to be. On the other hand for higher pressures most of the ions start so close to the parent ion where its field is large compared to that of any feasible external field. This being the case very little effect of the strength of the external field should be expected.

TABLE II. *Residual ionization. Number of ions collected per cc per second per atmosphere.*

Field in volts per cm \ Pressure in atm.	24.95	93.
1.55	3.11	1.34
6.2	3.22	1.45
23.0	3.38	1.55
91.5	3.53	1.64
367.	4.00	1.77
1009.	4.42	1.99

The readings made when the γ-rays were turned to one side represent the difference in the residual ionization caused in the two chambers by cosmic rays and radioactivity of the chamber and room. This was large enough in the case of the upper two pressures to be read with a considerable accuracy. Also in the case of these high pressures, the ionization in the ionization chamber was large compared to that in the compensating chamber and consequently the fact that the latter is subtracted should not modify the values very greatly. These results are given in Table II. As is at once seen the effect of increase in collecting potential is essentially the same as with the γ-rays.