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Measurement of the Ionization Per Centimeter of Path by Individual Secondary Cosmic Rays[1]

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The paper describes measurements of the ionization caused by individual secondary cosmic rays and groups of rays in a vertical cylinder 15 cm high and 7.5 cm in diameter. The experimental results are represented by plotting $F(n)$ against n, where $F(n)dn$ is the number of rays or groups passing through the cylinder in an assigned time and giving rise to spurts containing between n and $n+dn$ pairs of ions. If $f(l)dl$ is the number of rays of path length between l and $l+dl$, the theoretical curve for $f(l)$ for single rays shows a discontinuous increase at a value of l equal to the length of the cylinder, and this is followed by a sharp decrease. This phenomenon enables one to ascertain on the $F(n)$ curve the value of n which corresponds to the length of the cylinder, and so to deduce the ionization per centimeter of path in spite of the existence of multiple rays and of unavoidable amplifying tube background. The value for argon comes out as 89 ions per centimeter at atmospheric pressure. This value includes the contribution cited by G. L. Locher as caused by the Auger effect. The corresponding values for nitrogen and oxygen are 61 and 57, respectively. By a further analysis of the results, and particularly of those giving simultaneous spurts of ions with two cylinders in line, the existence of multiple rays is actually verified. These rays contribute two-thirds of the total ionization observed in the cylinder, and constitute one-third of the total number of ionizing entities, groups and singles. By a consideration of their effects it is possible to reconstruct the high values obtained for the *apparent* ionization per centimeter of path by former observers who have deduced their values from ionization measurements combined with counter data and from fluctuation measurements.

INTRODUCTION

THE fact that secondary cosmic rays contain electrons and positrons of energies higher than those observed in radioactive substances causes the investigation of their ionization per centimeter of path to be a matter of considerable interest, particularly as indirect investigations of this number have given values ranging all the way from 36 to 165 for the ions produced per centimeter of path at atmospheric pressure, in air, for example.[2] The experiments here described constitute a direct attack upon the problem in that the plan involves the actual measurement of the ionization of the individual rays. The accuracy at present is not high, but modifications of the method designed to secure a better approach to precision measurements have been made and the results of such measurements will be reported in due course. The accuracy of the present measurements is sufficient to bring to light certain interesting features, to establish the ionization per centimeter of path as around 90 ions per centimeter at atmospheric pressure in argon (which would correspond to about 60 for air rather than about 150), and to demonstrate the importance of double and triple rays in having contributed to the reason for the higher figure found by certain former observers.

EXPERIMENTAL PROCEDURE

The essentials of the apparatus will be clear from Fig. 1. A vertical cylinder A was provided with a central insulated rod which was connected to an FP-54 Pliotron, which in turn was connected to a four stage amplifier operating a short period galvanometer which recorded upon mov-

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[1] Presented in preliminary form before the American Physical Society, at the New York meeting, February 24, 1933, and in greater detail before The American Philosophical Society, at Philadelphia, April 22, 1933.

[2] By counting the individual drops in a cloud chamber, values of the order 40 ions/cm in air have been obtained by D. Skobelzin, by G. L. Locher and by C. D. Anderson. On the other hand, from counter data combined with the magnitude of the total ionization per second in a vessel, W. Kolhörster and L. Tuwin, working jointly, also W. Messerschmidt, and T. H. Johnson, have obtained values ranging from 110 to 165 ions/cm.

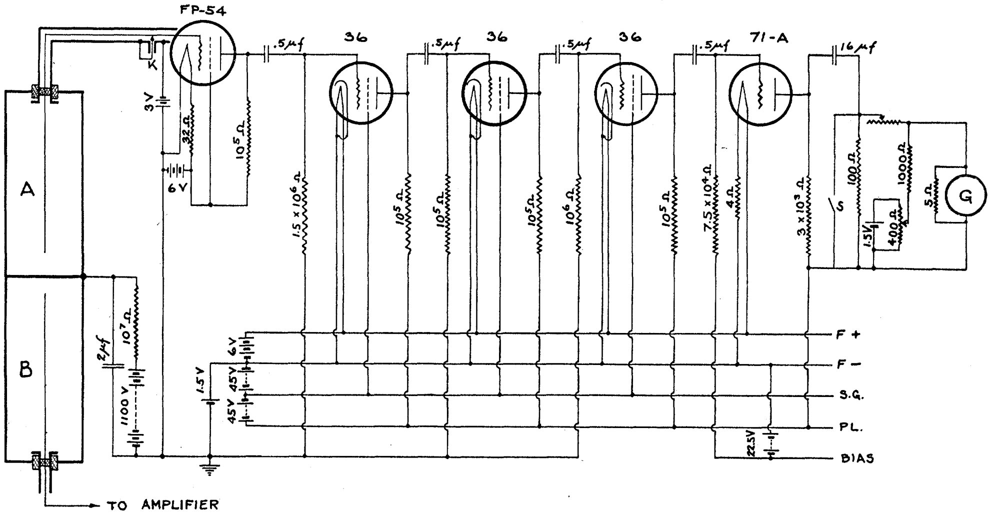

FIG. 1. Diagram of apparatus and electrical circuits.

ing photographic paper. The cylinder was filled with argon in the main experiments, to a pressure of 5 atmospheres in some cases and 10 atmospheres in others. A potential difference of 1100 volts was applied between the outer cylinder and the rod, so that the ions produced by an individual ray were swept across and caused to record upon the galvanometer. The more rapidly the ions are swept across, the sharper the kicks on the galvanometer and the greater the certainty in resolving them. The time taken to carry an ion from the central rod to the wall of the cylinder was of the order 0.05 second. The time for an electron is much less. The galvanometer used was of the Kipp and Zonen short period type modified to have a period comparable with 0.05 second.

For the purpose of securing additional information, two such systems as the above were employed, with the cylinders *A* and *B* arranged end to end, and with the galvanometers arranged to record upon the same photographic paper.

The main features of the electrical circuits will be clear from the data given in Fig. 1. The 1100 volt potential was applied through a resistance of 10^7 ohms to the outer cylinders which were connected to one terminal of a 2 microfarad condenser, whose other terminal was connected to the common point which served as the "earthed point" of the apparatus. In this way, battery fluctuations were ironed out. The insulated system was of course protected by a suitable guard ring system, and the FP-54 Pliotrons were incased in very thick copper cylinders with lids making electrical contacts with the cylinders all over their top surfaces through the agency of mercury. The reason for this was to secure very high conductivity in the shield for the purpose of eliminating electromagnetic disturbances of relatively low frequencies.

In spite of the fact that the apparatus was mounted in a ferro-concrete building of very rigid construction, the additional precaution of mounting the FP-54 tubes with their associated cylinders *A* and *B* on spring supports was found desirable and was adopted. The best test of the absence of spurious kicks produced by vibrations, electrical oscillations, etc., was that provided by taking a set of observations with the cylinders *A* and *B* at atmospheric pressure, in which case the ionization effects were reduced to relatively small amounts, and any spurious disturbances showed up. Since the kick obtained upon the galvanometer for a given number of ions collected depended upon the time of collection of the ions, and upon the time constants of the circuit to some extent, the calibration was carried out in such a manner as to minimize the error due to this cause. A known potential was applied to the external cylinder, *A*, for example, through a circuit by which the time of application of the potential could be controlled to an amount comparable with the time of collection of the ions. A knowledge of the coefficient of induction between the cylinder and the insulated system then enabled the sensitivity of the apparatus to be calculated as nearly as possible under the conditions of the actual experiments. It may be of interest to remark that variation of the time of application of the potential from zero to 0.1 second caused a variation of about 20 percent in the kick obtained on the galvanometer.

In order to avoid trouble from electrons emitted from the walls of the cylinders *A* and *B* by gamma-rays from the atmosphere, the cylinders were shielded by about 8 cm of lead. By observing the modification produced in the records by the addition of the lead and by observations made with radium outside the lead, one could verify that the trouble due to natural gamma-radiation was negligible, at any rate in the shielded condition.

THE RECORDS OBTAINED

The complete records obtained involved many thousands of counts and it is naturally only possible to give typical illustrations. Such are shown in Fig. 2. Each kick of the galvanometer is accompanied by a back kick. This is not a phenomenon of inertia but is properly inherent in the action of the amplifier as a little consideration will show. The measurements were made on the basis of the primary kicks and were calibrated accordingly. In Fig. 2, the spot should be regarded as travelling from right to left.

FIG. 2. Sample ionization records.

Fig. 2*E* represents a portion of a record taken with a cylinder 30 cm long and 4 cm in diameter filled with argon to 200 lb pressure. It is characterized by one very long kick which possibly represents an alpha-particle. The medium sized kicks are secondary cosmic-ray kicks. Fig. 2*D* is a trace for the same cylinder at atmospheric pressure and serves to show an upper limit for the magnitude of the background disturbances which are in part, at any rate, produced by the secondary cosmic rays. The sensitivity in the cases *D* and *E* is such that one millimeter kick on the original record corresponds to the instantaneous application of 4.0×10^{-5} volt to the central system. Fig. 2, *C* and *B*, represents simultaneous traces for two cylinders in line as in Fig. 1, each cylinder being 15 cm long and 7.5 cm in diameter filled with argon to 70 lb. pressure. The voltage sensitivity was about twice that for cases *E* and *D*. The arrow in case *C* indicates simultaneous kicks, and represents cases where a ray has passed through both cylinders. However, simultaneous kicks of this kind are unreliable of interpretation on account of the production of spurious coincidences by different rays which happen to coincide very nearly in time in the two cylinders. They are, however, reliable when used in the sense of *upper limits* to the number of real coincidences; and it is only in this sense that we shall use them. In Fig. 2*B*, the arrow indicates a portion of the trace of an alpha-particle for which the kick went completely off the photographic paper. Fig. 2*A* represents the same cases as *B* and *C* except that the pressure was one atmosphere.

ANALYSIS OF THE RESULTS

The full curve of Fig. 3*A*, shows, for a cylinder 15 cm long and 7.5 cm in diameter filled with argon at 5 atmospheres pressure, the values of $F(n)$ plotted against n where $F(n)$ is the coefficient of dn in the expression for the number of kicks in 2000 seconds which corresponds to a production of ions between n and $n+dn$ in number. The abscissae are the values of n. The curve

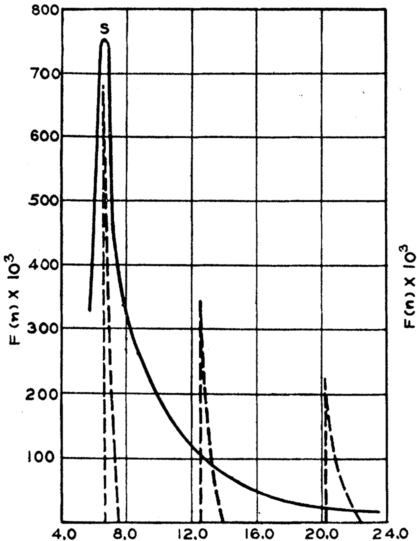

FIG. 3A.

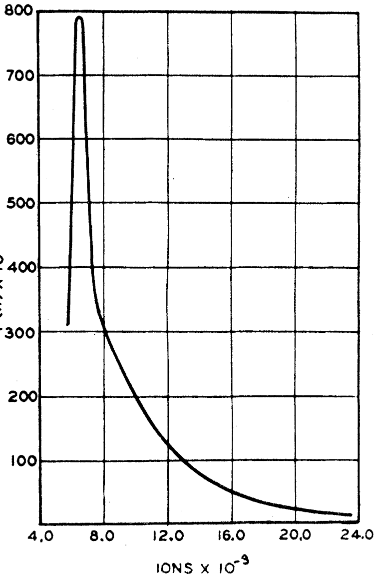

FIG. 3B.

represents the results of 2700 observations of kicks, about half of all the observations taken. Fig. *3B* represents the results of the other half of the observations. The two are given merely to show the extent of reproducibility of the results. The curves are not continued back to $n=0$ because for the smaller values of n the observations become obscured by the background disturbances of the FP-54 tube. As far back as they are drawn they are definite and reproducible to the extent indicated. If all of the rays were single rays of the same kind, the curve should correspond in form to the curve representing $f(l)$, the coefficient of dl in the expression for the number of rays which travel lengths between l and $l+dl$ in the cylinder for which the observations represented in Fig. 3 were taken. In Fig. 4, the theoretical curve is shown. The complete derivation of the formulae upon which this curve is based is given by the writer in a paper, *The Distribution of Cosmic-Ray Paths in a Vertical Cylinder*.[3] The constant A incorporated with $f(l)$ in the ordinates is the number of rays falling per second per unit vertical solid angle per unit of area perpendicular to the vertical.[4] Small a is the radius of the cylinder. The points P, Q and R correspond respectively to the diameter of the cylinder, the height of the cylinder and the longest line which can be drawn in the cylinder.

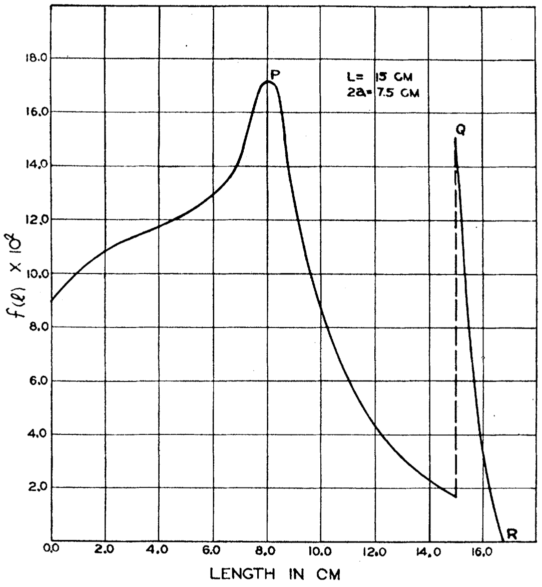

FIG. 4.

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[3] W. F. G. Swann, J. Frank. Inst. **216**, 559 (1933).

[4] Its value in Fig. 4 is taken as 0.72×10^{-2}, which value was obtained by Dr. Gordon Locher by means of Geiger counters in an adjoining room on the same floor of the laboratory as that in which the experiments were conducted.

The point Q is preceded by an actual discontinuity in the curve. The theoretical curve is drawn under the assumption that the intensity of the rays is proportional to $\cos^2 \theta$ where θ is the angle from the vertical, this law being an empirical expression of the facts of counter measurements. It must be remarked that the form of this law is representative of conditions in the open, while the observations here recorded were taken in a laboratory. However, the existence of peaks in the curve at P and Q and the positions of these peaks are phenomena depending upon the geometry of the cylinder rather than upon the law of distribution of the rays with θ. While a modification of the law of distribution would materially affect the relative heights of the ordinates of the curve for different values of l, it would not affect, except under very drastic conditions, the positions of the peaks. It will be mainly the positions of these peaks, and particularly that of the peak at Q which will be the basis of our comparison of the experimental and theoretical curves in what follows.

A casual inspection of Figs. 3 and 4 might suggest that the point S of Fig. 3 was to be associated with the point P of Fig. 4. However, a closer examination of the situation shows that such an association would be inconsistent with the facts. For if P of Fig. 4 corresponded to S of Fig. 3, then Q of Fig. 4 would correspond to C of Fig. 3. Now, for corresponding ranges dl and dn in the abscissae of the two curves $Tf(l)\, dl = F(n)\, dn$, where T represents the time interval (2000 seconds) to which the observations of Fig. 3 correspond. Moreover, if q is the number of ions per centimeter of path, $dn = qdl$. Hence $F(n) = (T/q)f(l)$. If we associate Q of Fig. 4 with C of Fig. 3, q becomes determined as n_c/L where n_c is the value of n at the point C. As a matter of fact, under these assumptions, q comes out as 850 and $F(n) = (2000/850)f(l)$. If we plot this quantity for the part of the graph to the right of C, we obtain the dotted curve shown near C in Fig. 3. This curve represents absolute magnitudes on the scale of the figure. The experimental curve shows no evidence of a discontinuity or peak to correspond to this condition. Experimental errors could not conceal such a peak if it really existed; for, such errors are all in the direction of giving spurious kicks, and so of increasing the apparent values of $F(n)$. We conclude that C cannot correspond to Q. If we choose such another point as D to correspond to Q, the theoretical contribution to $F(n)$ in the region of D would be given by the dotted curve there shown, and the absence of a peak would be still more difficult to explain. In fact, proceeding from the extreme right, the first and only place on the full curve of Fig. 3 which is capable of corresponding to Q is the point S. We must then conclude that Q and S correspond. The actual theoretical contribution to $F(n)$ resulting from this association is shown by the dotted curve in the vicinity of S. The absence of an absolute discontinuity in the experimental curve with accompanying broadening is only to be expected in view of the fact that $F(n)$ has to be determined by the utilization of finite ranges dn. The tube background plays an important part for values of n as small as those for the point S. On the other hand, the existence of an absolute and reasonably large discontinuity at Q, Fig. 4, combined with the sharp fall in the curve to the right of Q saves the situation as regards locating the abscissa of the peak in Fig. 3 in spite of the existence of the background. The peak should be able to show itself on the top of a background of ordinate much greater than its own, unless that background happened to have a sharp depression to cancel it, and this is highly improbable. The point which we wish to emphasize is that the abscissa of the peak at S has a significance which is unaffected by the background in spite of the fact that the actual experimental values of $F(n)$ there may be entirely unrepresentative of the ideal magnitudes freed from background.

The part of Fig. 3 which should correspond to P lies, of course, so far in the region of small kicks that it is entirely covered by the background; and, indeed, no attempt has been made to plot $F(n)$ in this region.

We must not expect to establish a close agreement between Fig. 3 to the right of S and Fig. 4 to the right of Q because, as will presently be seen, the right-hand portions of Fig. 3 are determined largely by doubles, triples, etc. These matters, like the existence of tube background have no effect upon the establishment of the correspondence between the abscissae of Q and S, and once that correspondence is established the number of ions per centimeter of path becomes determined. Its value comes out as *89 ions per centimeter of path for argon at one atmosphere* on the basis of a linear relationship with pressure, which assumption is valid for the range of pressure concerned, and particularly so for argon.

Evidence of Existence of Doubles, Triples, etc.

It is now of interest to examine certain other features of the portion of the curves, Fig. 3, which lie well to the right of *S*. Theoretically, on the view that the rays are singles, there should be one kick length which is the greatest possible and which corresponds to the longest path length attainable in the cylinder. As a matter of fact, experiments show a more or less continuous distribution of kick lengths extending up to values which would correspond to several hundreds of ions per centimeter of path at atmospheric pressure, although the number of such kicks diminishes with the size of the kicks. Suppose we fix on any kick length, such for example as that corresponding to the point *C*, as representative of a path comparable with the whole length of the cylinder. Now it will be obvious from the geometry of the situation that, on the basis of single rays, the number of rays which pass through the top of the upper cylinder and the bottom of the lower cylinder is of the order of one-quarter the number passing through the top and bottom of the upper cylinder. Hence, if we should choose *C* as representative of the rays which have travelled the whole length of one cylinder, we should find that about one-quarter of the corresponding kicks for the upper cylinder should show coincidences of equal numbers of ions for the lower cylinder. The experimental data for the point *C* give only about 0.04 instead of a quarter where a relatively liberal range of about 20 percent is allowed in judging the equality of coincident kicks. Fig. 5 shows as a function of *n* the actual value of the ratio of the number of equal coincident kicks to the number of the same size in the upper cylinder. In no case from the kicks corresponding to *S* to those of the largest size measured did the ratio approach 0.25. At first sight one might suppose that the reason for the above fact was to be found in the supposition that some of the rays were absorbed in the thin partition which separated the two cylinders. This partition, however, was only 2 millimeters thick, and we need only turn our attention to Fig. 6[5] which gives the theoretical variation of ionizing efficiency with the energy of the rays in the case of electron-like rays to see that absorption cannot be the cause. If we should assume that the rays corresponding to the point *C* were single electrons they would have to correspond to about 120 ions per centimeter of path for nitrogen. We know that β-particles of the order 3×10^6 volts velocity produce only

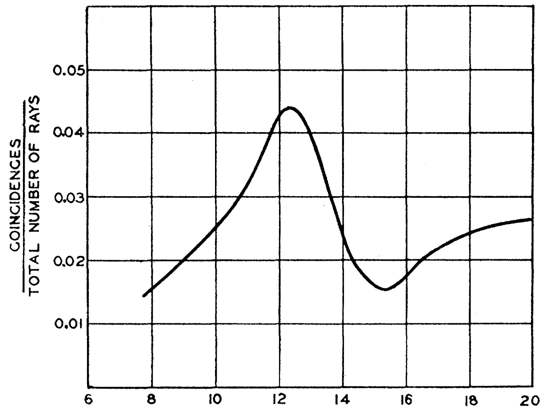

Fig. 5.

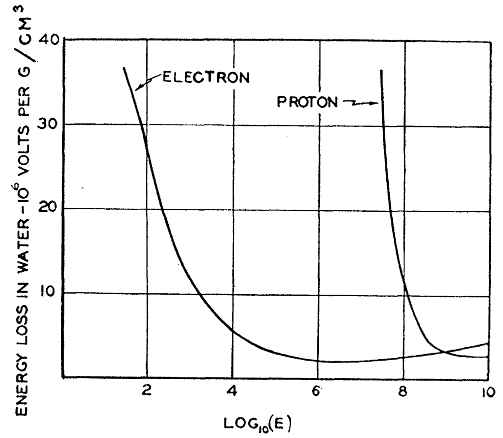

Fig. 6.

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[5] This curve is copied with a change of units from a curve given in a paper entitled *Some Photographs of the Tracks of Penetrating Radiation*, by P. M. S. Blackett and G. P. S. Occhialini, Proc. Roy. Soc. **A139**, 699–726 (1933).

about 30 ions per centimeter of path in nitrogen so that in order to account for 120 ions per centimeter of path, it is necessary to assume that the electrons correspond to an ordinate of the curve Fig. 6 which is at least three times the minimum. As a result we should have to assume for the electron energies greater than 10^{10} volts or smaller than 10^5 volts. With the former energy, the electrons would have no difficulty in getting through the two millimeters of brass partition, while, with the latter energy they would not be able to produce more than about three thousand ions, that is, less than corresponds to the measured kicks associated with the point C, which kicks correspond to about 12.6×10^3 ions. We get an interpretation more consistent with the facts if we assume that these rays are doubles or triples with a finite angle between them, and with these conditions it is easily possible to see that the angle might be such that while two rays could frequently pass through the whole length of a single cylinder, they could never pass through the whole length of the double cylinder. In general, of course, the phenomenon under discussion would show itself not by a complete absence of equal coincidences between the upper and lower cylinders but by a paucity of such coincidences in comparison with what might be expected from the simple interpretation on the basis of single rays. Fig. 5 shows a peak at the value $n=12.2\times 10^{+3}$. On the basis of the ionization per centimeter of path already established in the last section, this value 12.2×10^3 is just the value corresponding to a *double* ray which has travelled the full length of a single cylinder.[6] It is probable that the same geometrical considerations which operate to cause the discontinuity in $f(l)$ at Q, Fig. 4, for a length of ray equal to the length of the cylinder operate here also. If we concentrate our interest on pairs of rays, the sum of whose path lengths in each cylinder is equal to l, it is probable that the number of such pairs per unit range of l will show a discontinuity for the value of l which is *just* great enough to insure that the rays enter through the top of the upper cylinder and pass through the bottom thereof, in which case, of course, they would also pass through the bottom of the lower cylinder. On such a view the existence of the peak in Fig. 5 and particularly the value of its abscissa are confirmatory evidence of the presence of doubles in these measurements.

Of course it is not intended to imply that all of the single branches of the rays are alike. Some may be positrons and some electrons; and the energies may vary widely. However, large variations of energy in the region of minimum ionization or in the region of higher energies give, theoretically, relatively small changes in ionization. It is probably for this reason that the peak in Fig. 3 is as sharp as it is.

Arguments against the larger kicks being caused by protons are to be found in the fact that, as may be seen from Fig. 6, there is such a narrow range of energies for which protons have ionizing efficiencies appreciably greater than the minimum and yet have enough energy to penetrate the partition between the cylinders.

Ionization in Other Gases

Experiments were made for argon, nitrogen and oxygen in a cylinder 30 cm long and 4 cm in diameter. Fig. 7 shows the curves for $F(n)$. Here, on account of the small numbers of rays which travel the whole length of the cylinder, the peak corresponding to S, Fig. 3, is not to be expected

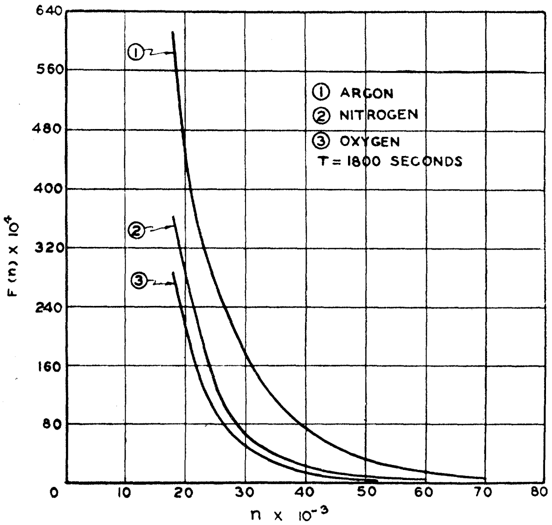

Fig. 7.

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[6] The effect of tube background is such as to render impracticable the realization of the corresponding peak for single coincident rays.

to show itself. However, one may assume that the distribution of rays, singles, doubles, triples, etc., is the same for all gases. Hence, if we choose three points on the three curves which correspond in the sense that the total number of rays to the right of those points is the same for all, and if we add up the ionizations for all of these rays in each case, the ratio of the numbers so obtained should give the *ratio* of the ionization per centimeter of path for single rays for the three gases in spite of the fact that the measurements are actually based upon doubles and triples. By choosing several corresponding sets of three points in this manner, the ratio of the ionization was obtained and this combined with the absolute value cited above for argon gives the following values for the ionization per centimeter of path at one atmosphere in the three gases concerned. The values are: for argon, 89; for oxygen, 57; for nitrogen, 61.[7]

Correlation with Former Data

Referring again to the data obtained with the shorter vessel, and assuming, as we have done, that S, Fig. 3, corresponds to Q, Fig. 4, it is possible to mark on Fig. 3 a point X which corresponds to R of Fig. 4. It is certain that all rays to the right of X represent multiples. Regardless of what they represent, however, we can obtain their total number N_1; and, from the sizes of the kicks to which they correspond, we can obtain their total contribution I to the ions per cc per second in the vessel. We find $N_1=3500$ and $I=2.2$ ions/cc/second, the latter value being reduced to nitrogen at atmospheric pressure. The experimental curve to the left of X must involve mainly singles. Except as regards the position of the peak, it is unreliable in quantitative significance on account of tube background. However, the theoretical curve Fig. 4 which is based upon the experimental value 0.72×10^{-2} for the A occurring as a factor in $f(l)$ serves as a basis to calculate the number N_2 of single rays which occur to the left of X. We find $N_2=6150$. Incidentally, therefore, it is of interest to notice that the number of multiples is a little more than one-third of the total number. In terms of the ionization per centimeter of path already determined, but reduced to nitrogen, we find that the total ionization caused by the single rays corresponds to $I_2=1.1$ ions/cc/sec. Thus, the total ionization per cc per sec. in the vessel is $2.2+1.1=3.3$ which is not far from the recent value 2.48 given by Millikan. No precision accuracy is, however, claimed for the former figure. The total number of ions produced per second in the whole volume of the vessel is 2200. If we divide this by the average ion path in the vessel, as obtainable from Fig. 4, and by the total average number of kicks per second which in this case is $(N_1+N_2)/4000=9650/4000$, we obtain 126. This then is the value that we might expect to be found for the ionization per centimeter of path in an experiment which failed to take account of the fact that the rays were in part multiples and which sought the quantity by dividing the ionization per second by the average ion paths and by the total number of rays. It falls well within the range 110–165 ions per centimeter already quoted as cited by former investigators who have used such methods. It is perhaps of interest, however, to realize that in the present work the same set of observations which treated in this way yields the high values can also through proper interpretation of the significance of the multiple rays be made to yield the smaller value 61 ions per centimeter of path in nitrogen.

In conclusion, I wish to acknowledge the services of my research assistant, Mr. W. E. Ramsey, who has made the actual observations cited in this paper. I also wish to express my appreciation of the services of Mr. Oscar Steiner, the Chief Mechanician, and his assistants in the construction of portions of the apparatus.

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[7] The ratio of ionization for argon to that for other gases is less than that found for the total ionization per cc as obtained by other observers. It is to be noted, however, that the ratio of the initial recombination loss in oxygen and nitrogen to that for argon is a function of the collecting time, which is particularly short in the present experiments.