The Production of Photons Relative to Ionization by Collision in a Townsend Gap

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Measurements were made in a Townsend gap to determine the average number of photons liberated by an electron for each secondary electron it liberates. In H_2, this number was found to decrease rapidly with increasing ratio of field strength to gas pressure in the range from 50 to 150 volts/cm/mm, and at pressures of the order of 1 mm. Determination of the absolute number of photons per electron depends on the unknown efficiency of the photoelectric cell used to count the photons. However, this number is estimated as of order unity. The effective radiation has an absorption coefficient of 0.55 cm^{-1} at a pressure of 1 mm of Hg. This large coefficient indicates that only those photons of rather high energy were counted. There is corroborative evidence that the brass surface of the photoelectric cell had a high work function. Thus only high energy photons would be expected to register.

INTRODUCTION

PHOTO-IONIZATION is increasingly accepted as an active mechanism responsible, at least in part, for the appearance of the second Townsend coefficient. In 1934, Cravath,[1] investigating the corona discharge, found that photoelectric effects were produced both in the gas and at the cathode. Dechene,[2] in the following year, showed the same phenomena to be present in corona and sparks. Kenty,[3] working with the positive column, and Greiner,[4] with Geiger counters, also contributed important evidence of photoelectric action. Photoelectrons produced in the gas by a spark were found by Raether[5] who detected them with a cloud chamber. The studies of Bowls[6] and Hale[7] have indicated that in certain cases the second Townsend coefficient can be attributed almost entirely to photoelectric effects at the cathode. Recent work on corona discharge[8-11] by investigators at the University of California has shown the dependence of this phenomenon on photoelectric effects in the gas. Raether's[12] investigations, and Loeb and Meek[13] in their book, have demonstrated that the streamer

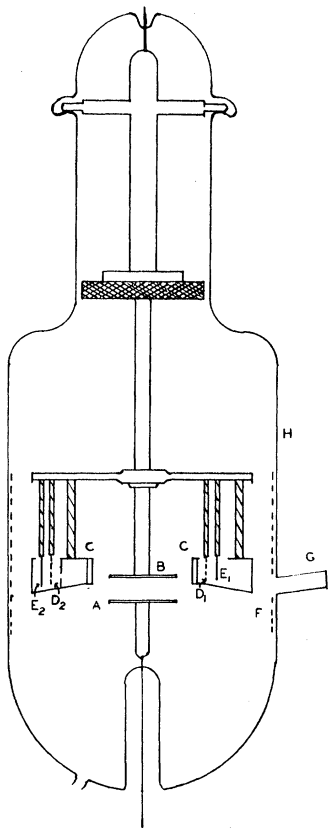

FIG. 1. Arrangement of chamber. *A*, cathode; *B*, anode; *C*, "doughnut;" D_1, D_2, collecting screens; E_1, E_2, measuring electrodes; *F*, grounded screen; *G*, quartz graded seal and window; *H*, Pyrex envelope.

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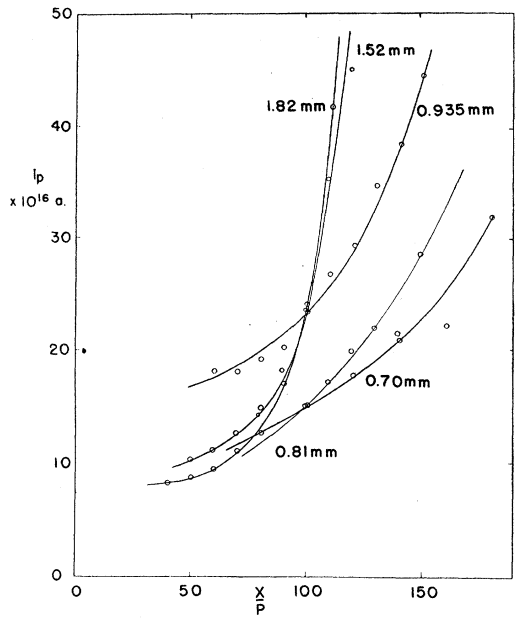

FIG. 2. Photoelectric currents at pressures of 0.70 mm, 0.81 mm, 0.935 mm, 1.52 mm, and 1.82 mm of Hg as functions of X/p.

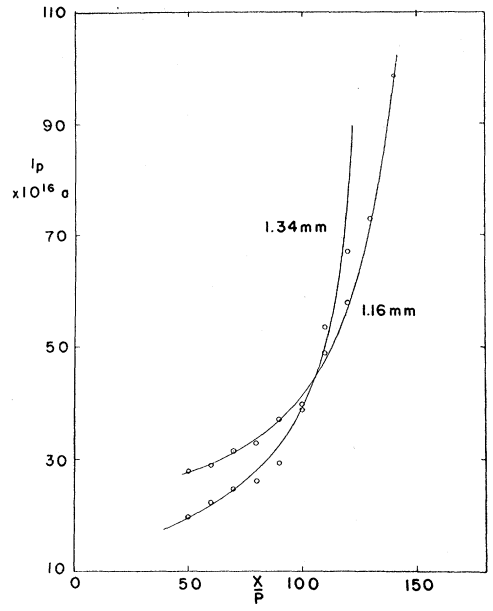

FIG. 3. Photoelectric currents at pressures of 1.16 mm and 1.34 mm of Hg as functions of X/p.

theory of spark discharge requires the assumption of an adequate supply of photoelectrons. Penning[14] has made calculations of the efficiency of electrons in ionizing and exciting gas molecules, these efficiencies being given as functions of field strength divided by pressure (X/p in volts/cm/mm). However, he was forced to use data of a doubtful nature and to extrapolate the data to extreme values.

In view of the incomplete nature of the above data, it was felt desirable that experiments be performed which would give an indication of the quantity of photons produced in a Townsend discharge. This paper sets forth the results of such an investigation, the gas used being H_2. Measurements made by Dr. L. H. Fisher in a number of other gases will be reported in the near future.

Consider a function θ defined as the number of photons produced by an electron in traveling one cm in the field direction of a discharge. In analogy with Townsend's α it is to be expected that

$$\theta/p = F(X/p). \tag{1}$$

From θ and α we may construct a function

$$n(X/p) = \theta/\alpha. \tag{2}$$

[14] F. M. Penning, Physica 5, 286 (1938).

This represents the number of photons produced by an electron for each secondary electron it produces. The function $n(X/p)$ lends itself readily to the calculations to follow. θ, α, and n are defined for a uniform field, in which case X/p determines the mean energy of the electrons.

Let i_0 be the initial electron current liberated from the cathode of a plane-parallel gap, which cathode is illuminated with ultraviolet light from a mercury arc. Then in the interval dx, at a distance x from the cathode, $i_0\alpha e^{\alpha x}dx$ secondary electrons will start. Hence, in this interval, $ni_0\alpha e^{\alpha x}dx$ photons will be produced in the gas. The measuring apparatus will count only those photons which pass through a slit system and liberate electrons from a brass electrode. Thus the solid angle subtended by the slit at each point of the discharge must be calculated. It is assumed that the photons are directed isotropically. At the low pressures (of the order of 1 mm of Hg) necessary in this experiment, diffusion of the electrons becomes appreciable and must be included in the calculation. It is also necessary to correct for the absorption of the photons by gas molecules. This correction, to a sufficient accuracy, is made by a factor $\exp[-\mu_0 P\rho]$ where μ_0 is the average absorption coefficient at 1 mm of

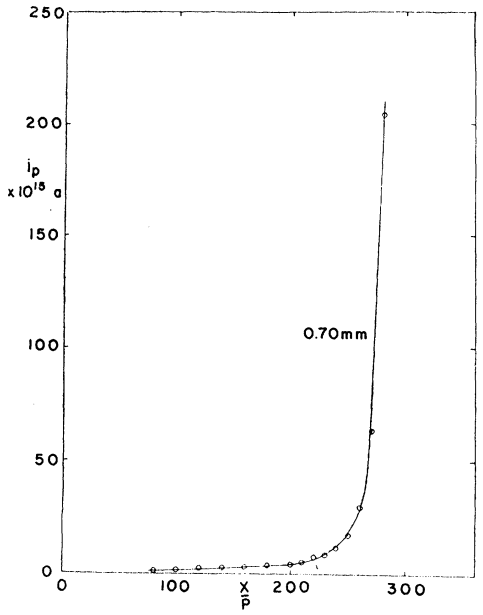

FIG. 4. Photoelectric current at 0.70 mm of Hg for X/p up to 280.

Hg and ρ is the distance from the center of the discharge to the collecting electrode.

Performance of the necessary integration leads to the expression

$$n\left(\frac{x}{p}\right)=\frac{34.0}{\eta}\frac{i}{i_e}\exp\left[\mu_0 p\rho\right]h(\alpha)$$
$$=n_p\exp\left[\mu_0 p\rho\right]. \quad (3)$$

Here η is the photo-efficiency of the brass counting surface, to be discussed later; i is the measured photoelectric current; $i_e=i_0e^{\alpha\delta}$ is the total electron current to the anode; $h(\alpha)$ is a function calculated from the geometry; and n_p is the quantity actually found by measurement, as the absorption coefficient is not known beforehand. μ_0 can be determined from values of n_p at two different pressures as well as from two electrodes at different distances from the discharge.

DESCRIPTION OF APPARATUS AND PROCEDURE

The chamber, originally designed by J. M. Meek, is shown diagrammatically in Fig. 1. A is the cathode, upon which ultraviolet light falls through the quartz window G. The anode B and measuring electrode system C, E, and D can be raised and lowered together by means of a screw-thread, ball-bearing race, and an iron armature turned by an external electromagnet. D is a screen kept at $+22.5$ volts to remove electrons liberated from the brass electrode. The "doughnut," containing the slit system, was kept at a constant potential of -67.5 volts. E, D, and C are insulated from each other by quartz supports. F is a nickel screen kept at ground potential. H is the glass envelope. The electrodes A and B are 4.0 cm in diameter, and are parallel to better than 0.5°. The inside diameter of the "doughnut" is 6.0 cm. Plate separations were read by means of a cathetometer.

The sets of collecting electrodes E_1, D_1 and E_2, D_2 are at 4.5 and 6.0 cm from the center, respectively, and were used as a pair to make measurements of the absorption coefficient. E_1 and E_2 could be connected to a Dolezalek electrometer through sulphur-insulated platinum switches. The sensitivity of the electrometer was 1500 mm/volt, and the capacity of the system including E_1, the cable, and the electrometer was 96.5 cm.

The anode B was kept at ground potential, and a negative voltage applied to A. This potential was supplied either by batteries or by a voltage stabilizer. An Heraeus mercury arc was used as a source of ultraviolet light. The image of a slit, illuminated by the arc, was focused on the cathode. The arc was operated on storage batteries and gave a quite constant intensity. The

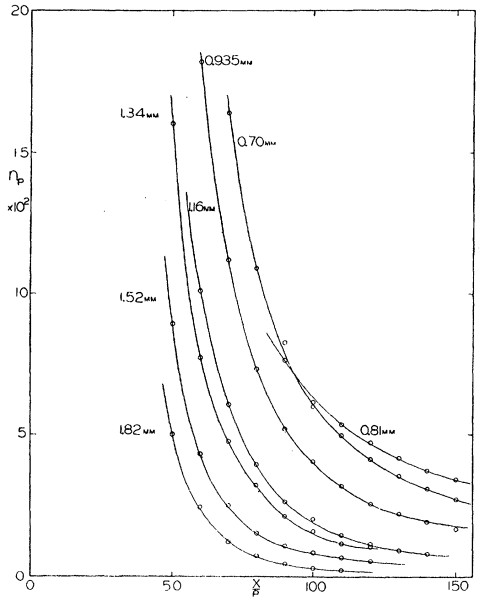

FIG. 5. n_p as a function of X/p for various pressures.

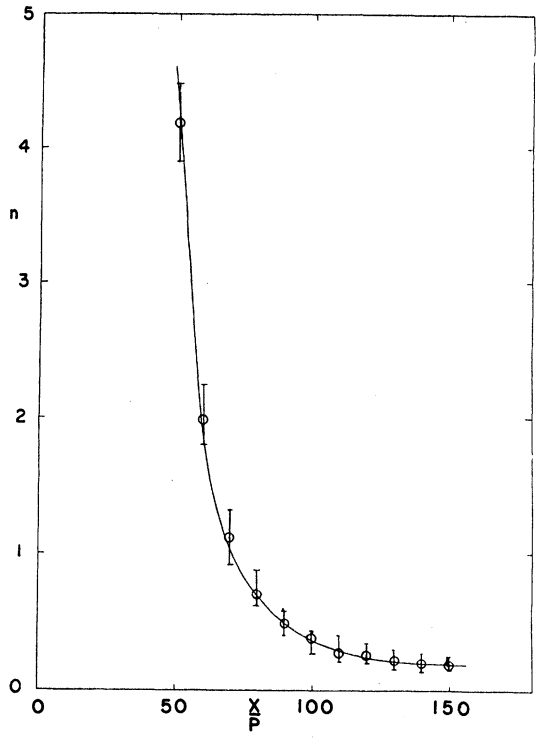

FIG. 6. The number of photons per secondary electron, n, as a function of X/p. Ordinates must be divided by the photoelectric efficiency to obtain absolute values. Vertical lines indicate spread.

visible image was rectangular, about 0.5 cm by 2 cm.

The photoelectric current was measured by the rate of charging of the electrometer. Backgrounds were determined with voltages applied but ultraviolet light cut off. They were occasionally as low as 10^{-16} ampere, and in most cases less than 0.1 of the photoelectric current. To keep the field distortion as constant and small as possible, all measurements were made at the smallest plate distance, 1.39 cm.

The total electron current to the anode was determined for each photoelectric measurement. This was necessary since the "doughnut" produced considerable field distortion. The plate separation could not be made less than 1.39 cm without interfering with the beam of ultraviolet light. Thus, measurements on the linear portion of the $\ln i_e/i_0$ *vs.* plate distance curve were impossible for X/p in excess of 110. Values of α under these conditions were determined by measuring i_0 at lower X/p and using this quantity and the total electron current i_e at the X/p desired. It is interesting to note that in spite of the large and variable field distortion, the graphs of $\ln i_e/i_0$ *vs.* plate distance are unmistakably linear at low X/p. The current i_e was determined by reading the voltage drop across a 10^8-ohm S. S. White resistor, or if too large for this, a 10^7-ohm I. R. C. calibrated resistor.

The chamber was baked out at 200°C and 10^{-5} to 10^{-6} mm of Hg for several hours. Measurements were made in two fillings of the chamber. Tank H_2 was passed over Cu at 350°C and then through a spiral liquid air trap. The chamber, of 6 liters volume, was filled to pressures of 1 to 2 mm of Hg in a period of approximately one-half hour. A McLeod gauge was used to read pressures. At no time was the chamber opened to the rest of the vacuum system without the presence of liquid air around the trap.

EXPERIMENTAL RESULTS

Measurements were made from X/p 40 to X/p 150. In one case the current was followed up

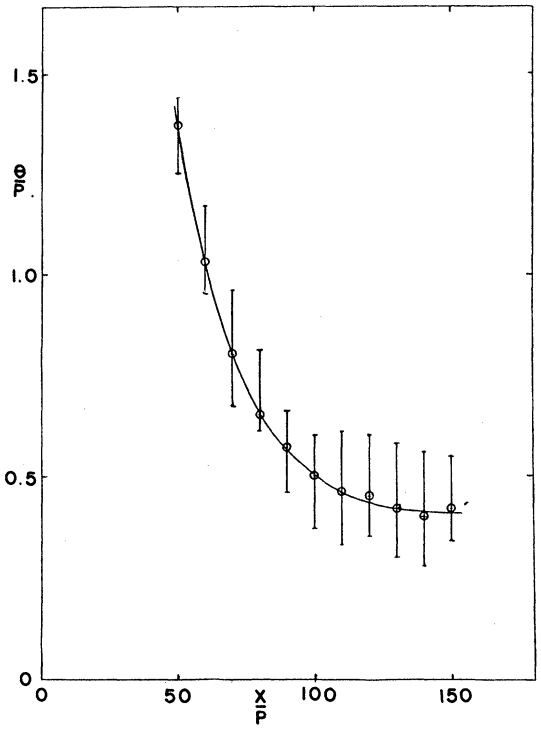

FIG. 7. The number of photons produced per cm per mm of Hg, θ/p, as a function of X/p. Ordinates must be divided by the photoelectric efficiency to obtain absolute values. Vertical lines indicate spread.

to an X/p of 280. The observed variation of photoelectric current at various pressures is shown in Figs. 2 to 5.

Values of n_p were calculated from the observed data and the function $h(\alpha)$. These values are given in Fig. 6 in arbitrary units. To obtain absolute quantities they must be divided by η, the photoelectric efficiency of the brass counting surface, which is unknown.

Independent determinations of the absorption coefficient, one at constant plate separation and the other at constant pressure, give 0.55 cm^{-1} and 0.42 cm^{-1}, respectively, at one mm of Hg. Correction of n_p for absorption brings the curves together, as shown in Fig. 7. The spread in values is indicated by the vertical lines. This spread is comparable with that in the measured α.

DISCUSSION AND CONCLUSION

Penning[14] has made calculations of the percentages of electron energy picked up in the field which appear as excitation, ionization, and in other forms. He has plotted these percentages as functions of X/p. The result of dividing the excitation curve by that for ionization is a variation similar to that in Fig. 7. His curve would remain at high values for low X/p. The design of the present chamber precludes knowledge of conditions at low α, hence, low X/p, and so this aspect cannot be verified. A quantitative comparison with Penning's calculations would require a knowledge of two additional quantities: (1) the photo-efficiency of the counting electrode; (2) the fraction of the total excitation energy represented by those photons capable of releasing electrons from the electrode. These quantities are not known for the experimental arrangement under consideration.

Since the counting surface was not degassed, but was in equilibrium with H_2 at a pressure of one or two mm, a value of η approaching 0.5 is not unlikely. If we assume this as a rough estimate, then at an X/p of 80 and at 1 mm of Hg, we find θ is about one photon/cm. From extrapolated data of Townsend and Bailey,[15] Bradbury and Nielsen,[16] and the kinetic free path, it is found that the number of collisions made by an electron per cm of path in the direction of the field under the above conditions is of the order of 100. Thus the inelastic collisions resulting in photons of the energies here considered represent a percent or so of the total number.

Hale's[7] curves for γ in H_2, with Pt and NaH cathodes, show a photoelectric peak in the neighborhood of $X/p=140$. The absence of such a phenomenon in the present work may be explained by one or both of the following: (1) Such a peak may not appear with a brass electrode; (2) the brass electrode may have such a high work function that the photons responsible for the peaks found by Hale are not sufficiently energetic to register. Calculations of γ for the anode show it to be of the order of 0.001, a tenth or less of Hale's values. Thus the brass surfaces present in the chamber are not photoelectrically sensitive.

Raether[5] has reported an absorption coefficient in H_2 of 0.9 cm^{-1} at 760 mm of Hg. His measurements were made above 235 mm of Hg. Greiner[4] gives a coefficient equivalent to 1.4 cm^{-1} at 760 mm of Hg measured at pressures of the order of 100 mm of Hg. At such high pressures any component of radiation with an absorption coefficient as large as that found in the present work would not be measured. It thus appears that the brass electrodes have surfaces of a particularly insensitive nature and are affected by only the most energetic photons.

Weissler[17] has shown that in a positive point-to-plane corona in pure H_2 no pre-onset streamers occur. Since the present work indicates that in such a discharge photons are produced in an appreciable quantity, it can only be concluded that either they are not sufficiently energetic for photo-ionization in the gas, or are absorbed too slowly to contribute photoelectrons to the formation of a streamer.

In conclusion, the author wishes to express gratitude to Professor L. B. Loeb, without whose guidance this undertaking would have been impossible. He also thanks Dr. Leon H. Fisher for many helpful discussions, and Mr. E. H. Guyon, glassblower, for his patience and skill.

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