Experimentally, we can evaluate $\alpha_i x_0$ and $\alpha_i X$ from studies of i_f/i_0 as a function of X. Thus, we know H. Similarly, we can evaluate D_m and G from a study of the variation of τ_1 with X. Hence, all quantities on the right side of Eq. (32) can be measured experimentally, and so a plot of the right side against the quantity $GX^2/\pi^2 D_m$ should give a straight line with a slope of $\alpha_m \gamma_r f_{esc}$ and a y intercept of $\alpha_m \gamma_m f_{esc}$. This is the method used to interpret some of the experimental data presented in II.

I. DISCUSSION AND SUMMARY

The form of the slow component of current, $i_s(t)$, in a pulsed Townsend discharge is closely described by a single exponential plus second term of higher time constant much smaller in amplitude. This term is negative in amplitude when the metastables initiate a current by releasing electrons in the process of bombarding the cathode. The amplitude is positive (i.e., adds to the first term) when the electrons are released through photoelectric action of photons from metastables converted in the gas.

From a study of experimental current patterns one can get with little trouble the fundamental time constant of decay, τ_1, of the metastables in the gap. This is valuable, because by studying the variation of τ_1 with electrode spacing and gas pressure, the diffusion constant and volume destruction probability of metastables are readily obtained. In addition the quantities $\alpha_m \gamma_m$ and $\alpha_m \gamma_r$ can be obtained. Applications of these methods of analysis are described in II.

The author wishes to express his appreciation to Miss C. L. Froelich and her co-workers for assistance in carrying out computations.

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Studies of γ-Processes of Electron Emission Employing Pulsed Townsend Discharges on a Millisecond Time Scale

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The relative amounts of electron emission from the cathode in a Townsend discharge caused by ions, photons, and metastables have been studied experimentally for several cathodes in argon, using pulsed-light stimulation of the discharge. The current initiated by metastables exhibits a slow build-up and decay, thus permitting easy separation from the faster rising effects of gas ionization and electron emission by photons and ions. Time constant studies of the slow component yielded a diffusion constant for metastable argon atoms of 45 cm^2 sec^{-1} at one millimeter pressure. The efficiencies of electron emission by metastables and ions was found to be closely the same, while the quantum yield for photon emission was found to be generally smaller.

I. INTRODUCTION

ELECTRON emission from the cathode in Townsend or glow discharges is generally believed to arise from the bombardment of the cathode by ions, metastable atoms, and photons.[1,2] These processes are commonly called the γ-processes, or sometimes the γ-mechanism, after the coefficient γ used in the Townsend equation to describe the part of the amplification of an electron current between electrodes in a gas attributable to these processes. The experiments in this paper were directed towards an evaluation of the relative amount of electron emission produced by the ions, the metastables, and the photons in the case of argon gas with several cathode materials. An incidental by-product of these studies was a determination of the lifetime of metastable argon atoms.

The method employed was similar to that described by Engstrom and Huxford.[3] A Townsend discharge was stimulated by photoelectrons generated by a shuttered light beam shone on the cathode of a gas-filled tube, and the transient character of the resultant current between the electrodes was observed by an oscilloscopic technique. The current is found to be composed of a component closely in step with the stimulating light pulse and a component which lags by an amount of the order of a millisecond. The second component is initiated by the action of metastables, which have lifetimes in the discharge space of this amount of time. The fast component includes the primary electron current amplified by gas ionization and electron emission from the cathode caused by ion and photon effects, all of which reach a steady-state value in a time of the order of ten microseconds.[4] From an analysis of these patterns the fractions of the electron emission produced by metastables and by ions and photons were obtained.[5]

[1] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939).
[2] M. J. Druyvesteyn and F. M. Penning, Revs. Modern Phys. **12**, 87 (1940).
[3] R. W. Engstrom and W. S. Huxford, Phys. Rev. **58**, 67 (1940).
[4] A parallel study of pulsed Townsend discharges on a microsecond time scale, in which these effects can be resolved, has been carried out by J. A. Hornbeck of these laboratories.
[5] A theoretical analysis of transient form of the current in the Townsend discharge under these conditions is described in a companion paper (hereafter referred to as I), and reference will be made to the relations derived in that paper.

The relative emission efficiencies of photons and metastable atoms were measured by an experiment in which metastable atoms are converted into radiating atoms by irradiation of the discharge space with light of the proper wavelength.

II. GENERAL PROCEDURE

The usual procedure employed in Townsend experiments[6] is to measure the current, i, between plane-parallel electrodes when a primary photocurrent, i_0, is liberated by light shone on the cathode, and the cathode-anode spacing, X, is varied with the electric field, E, maintained constant. The measured values of i/i_0 are then fitted to the Townsend equation,

$$i/i_0=\exp[\alpha_i(X-x_0)]/1-\gamma(\exp[\alpha_i(X-x_0)]-1), \quad (1)$$

where α_i is the number of electron-ion pairs generated per electron per cm of path in a direction perpendicular to the electrode surfaces and is commonly called the First Townsend Coefficient, x_0 is the minimum value of the electrode spacing at which ionization can occur, and γ is defined loosely as the number of electrons liberated at the cathode per ion striking it.

For our purposes γ is defined more specifically as the number of electrons which are liberated at the cathode and enter the discharge stream per ion formed in the gas. Such a definition permits us to include in γ the metastable and photon contributions by writing

$$\gamma=f_{esc}\left\{\gamma_i+\frac{\alpha_r}{\alpha_i}f_{rk}\gamma_r+\frac{\alpha_m}{\alpha_i}[f_{mk}\gamma_m+f_{mr}f_{rk}'\gamma_r]\right\}, \quad (2)$$

where γ_i, γ_r, γ_m = number of electrons liberated at the cathode per ion, per photon, and per metastable, respectively; α_i, α_r, α_m = number of ions, photons, and metastables produced per cm per electron; f_{esc} = fraction of the electrons liberated at the cathode which escape the back diffusion effect and enter the discharge stream; f_{rk}, f_{mk} = fraction of the photons and metastables generated in the gas which reach the cathode; f_{mr} = fraction of the metastables generated in the gas which are converted to radiating atoms; f_{rk}' = fraction of the photons from these radiating atoms which reach the cathode.[7] In this expression f_{rk}, f_{mk}, f_{mr}, and f_{rk}' are not independent of X; and so γ is not strictly a constant when one measures i/i_0 *vs* X, as in an ordinary Townsend experiment.[8]

In our experiments the fast component of current is assumed to be described by a Townsend equation with the γ-coefficient given by γ_f, where

$$\gamma_f=f_{esc}[\gamma_i+(\alpha_r/\alpha_i)f_{rk}\gamma_r]. \quad (3)$$

The total current is described by a Townsend equation with $\gamma=\gamma_f+\gamma_s$, where

$$\gamma_s=f_{esc}(\alpha_m/\alpha_i)(f_{mk}\gamma_m+f_{mr}f_{rk}'\gamma_r). \quad (4)$$

By means of light of appropriate wavelength shone on the space between the electrodes, metastable atoms can be converted into radiating atoms. In this way we were able to vary, in effect, the quantities f_{mk} and f_{mr}, and from the resultant variation in γ_s compute a value of γ_r/γ_m. The small value we found for this ratio indicates that at high values of E/p_0, where $(\alpha_r/\alpha_i)f_{rk}<1$, the second or photon part of γ_f is small, and therefore the variation of γ_f with X is negligible. Thus, in this high E/p_0 region we fitted the fast component of current to the Townsend equation assuming a constant value of γ_f throughout the range of X variation. From this fit, $\exp[\alpha_i(X-x_0)]$ was obtained and used to evaluate $\gamma_f+\gamma_s$ from the values of the total current; and γ_s as thus obtained was found in general not to be constant with X.

Examination of the Townsend equation quickly reveals that the accuracy with which γ can be evaluated is closely dependent on the accuracy with which the term $\exp[\alpha_i(X-x_0)]$ is known. The latter term is most accurately evaluated when the Townsend experiment is conducted on a surface with a low value of γ, because then the denominator in the Townsend equation does not depart appreciably from a value of unity until large values of X are reached. We therefore found it expedient to make our measurements on two or more surfaces of different γ-values in tubes interconnected so as to have exactly the same gas filling. Then the quantity $\exp[\alpha_i(X-x_0)]$ was evaluated from the data taken on the low γ-surface and used to evaluate both γ_f and γ_s from the data taken on the high γ-surface.

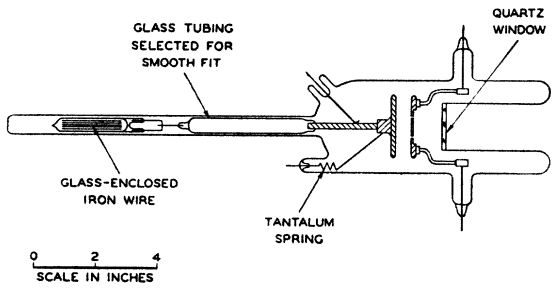

FIG. 1. Townsend tube used in later experiments. The drawing is simplified for purposes of clarity. The anode (right-hand electrode) is supported in three places, instead of two as shown, with the inner section held with two glass-insulated wires. The upper wire contact to the cathode support rides in a slot to prevent rotation. Holes in the inner glass tubing provide a means of pumping the left-hand side of the tube. The inside of the tube is coated with Aquadag with a ring ½ in. wide left clear in the region near the electrodes. Connections are provided to each half of the coating.

[6] An excellent summary of studies in the rare gases is given by A. A. Kruithof, Physica 7, 519 (1940).

[7] This expression for γ is obviously simplified, because we have lumped into one both types of metastables ($^3P_0$ and $^3P_2$) and into one all types of photons. Furthermore, f_{esc} may be different for electrons released by the various processes. In addition there may be conversion of radiating atoms back to the metastable states, a process which probably becomes important at higher pressures.

[8] Although most previous experimenters have assumed γ to be a constant in their interpretation of Townsend data, this has probably not affected seriously their values of α_i, since the evaluation of α_i from experimental data is rather insensitive to the value of γ employed.

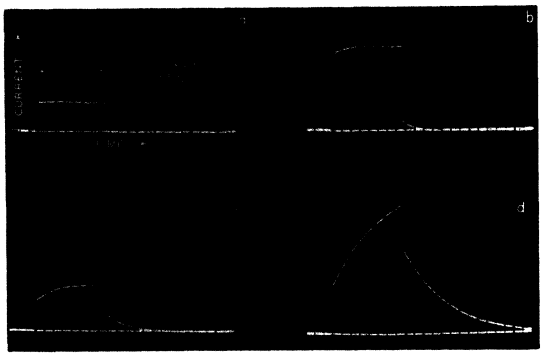

FIG. 2. Typical oscillograms of the current in a Townsend discharge with pulse light stimulation. The traces were taken with a fixed electrode separation and increasing values of applied voltage going from *a* to *d*. The amplifier gain was reduced 5× for traces *c* and *d*. Trace *a* corresponds to a current consisting entirely of photoelectrons released from the cathode by the stimulating light. The other traces show the effect of gas amplification and γ_f-processes by the increase of the in-phase component and the effect of the γ_s-processes by the appearance in successively larger amounts of a delayed component.

Actually, it is very difficult to fit the Townsend equation to i/i_0—data from a surface with $\gamma \approx 0.25$, because the value of α_i has barely stabilized at the value of X at which breakdown occurs.[9]

In the first set of experiments we employed two tubes, one with a BaO—Ni surface (high γ) and the other with a nickel surface (low γ). In a second set of experiments four tubes were set up, three with surfaces of tantalum, molybdenum, and barium oxide on tantalum and one intended to be barium on tantalum. Unfortunately, the barium was accidentally lost in the processing and so this surface was essentially like the plain tantalum also. In fact, however, the pure metal surfaces undoubtedly did not represent atomically clean surfaces but were to some extent contaminated by adsorbed gases. Furthermore, we were unable to vary the gas pressure in the tubes without altering the cathode surface properties. Thus, we shall present here only a limited amount of γ-data. They are intended to illustrate the composition of γ for the surfaces as they were studied, which we recognize were neither in a clean nor necessarily in a very stable condition.

Our experiments were limited, in the main, to the higher range of E/p_0, i.e., from about 50 to 200 volts/cm ×mm, for two reasons. At lower values of E/p_0 the increased generation of photons make their contribution to γ_f sizable, and therefore γ_f can no longer be assumed constant with X. Furthermore, the higher gas pressures required for experiments at lower values of E/p_0 result in having a large fraction of the metastables destroyed in the volume rather than at the electrodes. Both of these effects make any measurements of Townsend currents much more difficult to interpret in the low E/p_0 region.

[9] The Philips workers showed that α_i varies periodically with x for small values of x and becomes constant only when $x>3$ to $5x_0$. This arises from a changing velocity distribution of electrons with x, and it is only when this distribution becomes independent of x that α_i becomes constant.

III. EXPERIMENTAL ARRANGEMENTS

Two types of Townsend tubes were used in the course of these studies. The first type was similar to that described by Engstrom and Huxford.[3] The second type of tube, shown in Fig. 1, has a smaller outside diameter so that both anode and cathode can be outgassed by rf induction heating. Wall charge effects are minimized by coating the interior walls of the tube with Aquadag. The coatings were in two halves, one connected to the anode, the other to the cathode potential.

The electrodes were two inches in diameter and one-eighth inch thick, with rounded edges. The anode in the first type was drilled with approximately 200 holes 0.013 in. in diameter grouped in the central area inside a circle $\frac{5}{8}$ in. in diamater. In the second tube the anode was made in two parts to permit separate measurement of the current to the central and to the outer parts of the electrode. The central part was made in the shape of a hexagon approximately 0.6 in. in "diameter" with 331 holes 0.016 in. in diameter. The inner half of the outer part was drilled with 864 holes of the same diameter. The current measurements to the two parts did not, in general, reveal anything very interesting, so for the most part the total current alone was measured.

By trial-and-error methods the cathode-supporting section of the tube could be adjusted so as to achieve a parallelism of the electrodes to about 0.1°. During bakeout and outgassing operations the supports sometimes sagged. If the angle increased to a value greater than 0.4°, the tubes were corrected. Electrode spacing was measured with a traveling microscope to a precision of about 0.01 mm.

Baking and outgassing operations were conducted alternately over a period of several days. With the apparatus cold a vacuum of 1×10^{-8} mm of mercury was indicated on an ionization gauge. The barium oxide surfaces were prepared according to conventional practice.[10] The pure metal surfaces were operated at high currents in a glow discharge. For molybdenum the "contraction" phenomenon was observed.[11] In the case of tantalum at high currents the discharge tended to go to the Kovar support on the rear side and no contraction effects could be produced. After several flushings with argon, a Batalum getter was flashed, gas was admitted at the desired pressure, and the tubes were sealed off. Pressure was measured at an accuracy of about 0.5 percent with a carefully calibrated McLeod gauge.

[10] The metal electrodes are coated with a mixture of $BaCO_3$ and $SrCO_3$ 0.5 mg per cm². During outgassing of the electrodes the carbonates are converted to oxides. Then with argon at a pressure of about 20 mm, a high frequency discharge from a spark generator is operated between the electrodes until the cathode reaches a state of constant activation. The sustaining voltage for a newly prepared surface can be as low as 55 volts.

[11] F. M. Penning and J. H. Moubis, Philips Research Repts. 2, 119 (1946).

A system of multiple seal-off constrictions and break-off tips described by Engstrom and Huxford[3] was incorporated to permit subsequent change in the gas pressure without exposure of the system to the atmosphere. In practice, however, when this was attempted, the cathode surfaces never appeared to retain their original emission efficiencies, and so one was then left with the very small area of opening in the shattered break-off tips for use in pumping during the subsequent preparation of the surfaces.

In all Townsend experiments it is of prime importance to use gas of the highest purity. Small impurities have two kinds of effects: (1) they may destroy the argon metastables by collisions of the second kind, and (2) they may affect the cathode emission efficiency. Our main effort toward purification consisted of exposing the gas[12] to a surface of barium metal flashed from a Batalum getter and then passing it through two liquid nitrogen traps, one of which was in the form of a long helical coil. Some measure of the purity could be obtained from the time-constant studies described in Sec. IV. Kruithof and Penning[13] have described techniques of purifying rare gases by operating a discharge between barium or other electrodes. Although we tried similar techniques, we cannot definitely state that beneficial effects were observed generally, at least as measured by the lifetime of the metastables.

The source of stimulating light was an AH-4 high pressure mercury lamp, with its glass envelope removed, operated on dc. The light was shuttered by a rotating sector disk which produced a pulse five milliseconds in duration every one-thirtieth of a second. When the amount of light was ample, the slit behind the disk through which the light was directed could be reduced to 0.2 mm so as to give a rise time for the light pulse of about 20 μsec.

Current through the tube was measured by letting it flow through a resistor from one electrode to ground, amplifying the resultant IR drop, and displaying on a cathode-ray oscilloscope. In order to permit measurement of the smallest possible current, careful attention was paid to the problem of inherent noise in the amplifier. By using a selected tube for the first stage operated on batteries, the amplifier noise, with a grid input resistor of 200,000 ohms, was about 10 microvolts or the equivalent of 5×10^{-11} amp flowing through this resistor. Thus, to measure a current through the tube with an accuracy of 0.5 percent, the current had to be roughly 200 times this amount, or 1×10^{-8} amp. Space charge effects began to distort the observed patterns at currents greater than about 2×10^{-7} amp, and we had, therefore, only a twentyfold range of current over which accurate measurements were possible. An improved signal-to-noise ratio could, of course, be obtained by employing a larger grid resistor; but the resultant rounding of the pattern then made it impossible to separate clearly the fast and slow components of current. Typical patterns are shown in Fig. 2.

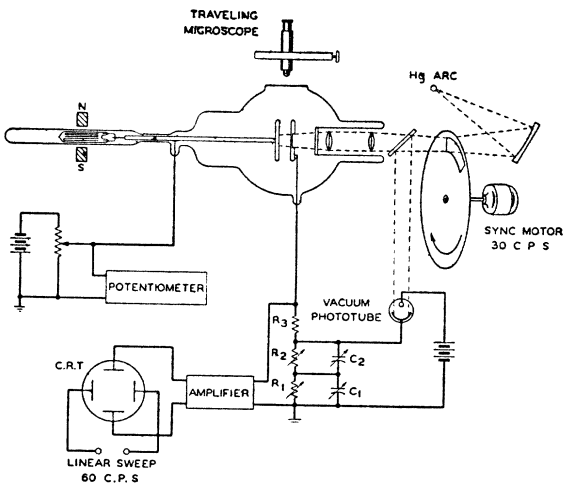

FIG. 3. Schematic diagram of arrangement of apparatus. The resistance of R_3 is large compared with R_1+R_2, so that the effect of the capacitance of C_1 and C_2 on the Townsend tube current is small. The horizontal sweep on the cathode-ray tube is operated at twice the disk frequency to provide a zero-line reference.

The actual current measurement was made by employing a null method. By means of a partially reflecting mirror, some of the light was directed into a vacuum phototube, which then generated a current pulse exactly in step with the primary current in the Townsend tube. This current flowed through two resistor-capacitor combinations, R_1C_1 and R_2C_2, as shown very schematically[14] in Fig. 3, by means of which a voltage pulse could be formed having a shape and size very similar to that of the total Townsend current but opposite in sign. The fast component of the Townsend current could usually be matched closely with an RC combination having a time constant of from 0 to 30 sec. A large part of the slow component could be matched with an RC combination having a time constant from 0.1 to 30 milliseconds. When these components were adjusted to a "best" fit to the Townsend current, there remained nearly always a component negative in amplitude and intermediate in time constant.[15] The amplitude of this component was measured by the decrease necessary in the fast component to bring the current trace up to the baseline. Under favorable conditions the fast component could be measured with an accuracy of 0.2 percent, and the slow time constant with an accuracy of 2 percent.

[12] One liter flasks of the "spectroscopically pure" grade were purchased from Air Reduction Company and Linde Air Products. Mass spectrometric tests revealed no impurities above the level of detection of the instrument, which was about 0.005 percent for the common gases.

[13] A. A. Kruithoff and F. M. Penning, Physica 3, 515 (1936).

[14] The circuit was actually arranged in such a manner as to permit independent adjustment of the R and RC values of both the fast and slow components.

[15] See I for an interpretation of this component.

TABLE I. Sample data illustrating the computation of the fundamental time constant, τ_1, from the observed time constant T_1 by Eq. (5).

Applied potential (volts)	i_f (10^{-8} amp)	i_{s1} (10^{-8} amp)	i_{s2} (10^{-8} amp)	T_1 (10^{-3} sec)	τ_1 (10^{-3} sec)
76.5	2.28	1.20	−0.075	1.17	0.76
78.5	2.61	1.69	−0.078	1.29	0.77
79.5	2.87	2.05	−0.10	1.38	0.79
80.5	3.07	2.55	−0.11	1.46	0.78
81.0	3.17	2.89	−0.10	1.50	0.78
82.0	3.43	3.73	−0.12	1.65	0.78
83.0	3.80	5.09	−0.15	1.85	0.77
83.5	4.00	6.06	−0.18	2.00	0.77
84.0	4.29	7.34	−0.21	2.19	0.78
84.5	4.52	9.15	−0.21	2.45	0.78

IV. TIME CONSTANT STUDIES

The current-measuring apparatus described in the preceding section made it possible to make detailed time constant studies of the slow component of current with relatively little effort. The procedure employed was to measure the time constant of the slow component, T_1, and the amplitudes of the fast (i_f), slow (i_{s1}), and intermediate (i_{s2}) components for various applied voltages at a series of electrode spacings. As explained in the companion paper, T_1, can then be related to the fundamental time constant of decay of metastables in the gap, τ_1, through the relation,

$$\tau_1 = T_1[(i_f+1.3i_{s2})/(i_f+1.3i_{s2}+i_{s1})]. \quad (5)$$

The value of τ_1 obtained from this relation should be the same for a given electrode-spacing independence of the applied voltage as well as the electrode material, provided the electrical effects caused by the destruction of the metastables originates at the cathode (see I). In other words, the slow component must arise from electron emission caused either by direct impact of the metastables on the cathode, or by the conversion of metastables into radiating atoms in the gas from which the light radiation causes photoelectric emission at the cathode. Should the slow component of current arise from an ionization of impurity atoms by collision with the metastables (Penning effect), then analysis shows the value of τ_1 should be calculated from the observed quantities by a different equation. Thus, τ_1 from Eq. (5) will not be independent of the voltage.

For the most part Eq. (5) appeared to be applicable in all the argon studies. (See sample data given in Table I.) Occasionally, for large values of T_1/τ_1, i.e., three or larger, deviations as large as 25 percent were found. The voltages at which such large ratios are observed are usually close to breakdown, and the accompanying unsteadiness of the pattern along with possible space charge distortions might explain the failure of the relation.

The quantity τ_1 represents the fundamental time constant of decay of metastables and is related to the diffusion constant, D_m, and the probability of volume destruction of metastables per second in the gas, G, by the relation,

$$1/\tau_1 = (\pi^2 D_m/X^2)+G. \quad (6)$$

Plots of $1/\tau_1$ *vs* π^2/X^2 should, therefore, yield straight lines with slopes given by D_m and a y-intercept equal to G. Several such plots are shown in Fig. 4 for various pressures in argon. Both the slopes and intercepts are seen to vary with pressure. The slopes fit a $1/p$ variation, as might be expected for the diffusion coefficient. The points for different electrode materials are seen to fall satisfactorily on the same line, which is gratifying, because the surfaces had widely different γ_m-values and so the measurements were made at widely different values of applied voltage.

The diffusion coefficient for argon metastables in argon, D_m, as obtained from these measurements is 45 ± 4 cm^2 sec^{-1} for a pressure of one millimeter at 25°C.[16] This may be compared with the diffusion coefficient, D_n, obtained by Hutchinson[17] for radioactive argon atoms of mass 41 in normal argon (largely mass 40), which is 139 cm^2 sec^{-1} when reduced to this pressure and temperature. If we assume that in a collision between a metastable and an unexcited argon atom the "radius" of the normal atom, r_n, has the same value as in a collision between two unexcited atoms, then, if r_m is the "radius" of the metastable atom, we

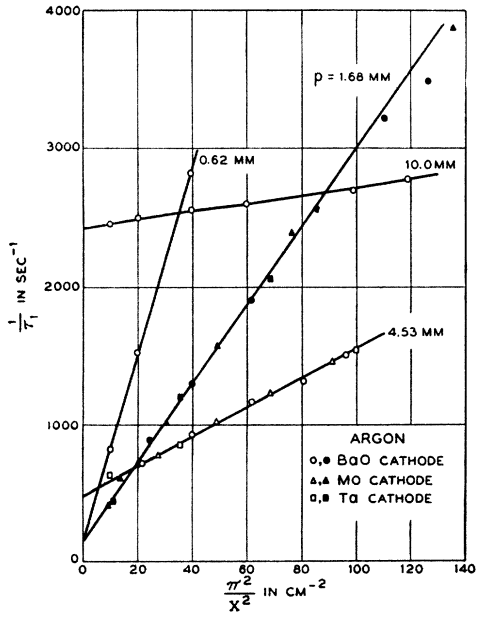

FIG. 4. Plots of $1/\tau_1$ *vs* π^2/X^2 for argon metastables in argon. The slopes of these curves give D_m, while the y intercepts give G. The measurements were made at room temperature ($T=25$°C).

[16] The pressure here is not the reduced pressure p_0, defining the concentration of gas at 0°C. We did not reduce the data here to 0°C, because we do not know how D_m varies with temperature.

[17] F. Hutchinson, J. Chem. Phys. **17**, 1081 (1949) (argon); W. Grath and E. Sussner, Z. physik. Chem. **193**, 296 (1944) (neon); and W. Grath and G. Dickel, Z. Elektrochem. **47**, 167 (1941) (krypton and xenon).

have from kinetic theory that

$$D_n/D_m=(r_n+r_m)^2/(2r_n)^2. \quad (7)$$

This yields $r_m/r_n=2.52$, which appears to be a reasonable value.

Similar time constant studies carried out in neon and xenon gave values of $D_m=120\pm10$ cm^2 sec^{-1} for neon, and $D_m=13\pm1$ cm^2 sec^{-1} for xenon, both at one millimeter pressure and a temperature of 25°C. These can also be compared with diffusion coefficients obtained by isotope tracer techniques[17] and values of r_m/r_n can be computed, which come out to be 2.45 for neon and 2.22 for xenon.

Once the value of the diffusion coefficient had been established for argon, the plot of $1/\tau_1$ *vs* π^2/X^2 in any later experiment served as a useful check of the proper behavior of the metastables. The effect of the presence of impurity molecules in the gas which destroy the metastables on collision with them but are not ionized in the process can be detected by an increase in the value of the y intercept in a plot of $1/\tau_1$ *vs* π^2/X^2.

In one instance the presence of a large amount of nitrogen (probably in a concentration of about 0.1 percent) produced a more striking effect in that these molecules destroyed all the argon metastables in a time of 100 microseconds. However, the nitrogen molecules when thus excited ended up in a metastable state, as evidenced by the fact that a slow component of current was observed in the Townsend tube of milliseconds duration. When a study of the fundamental time constant, τ_1, of this component was made, however, it was found that the lifetimes of the metastables in this case were substantially different from that of the argon metastables. The data gave a diffusion constant for nitrogen metastable in argon of 157 cm^2 sec^{-1} at one-mm pressure and 25°C, with an immeasurably small volume destruction.

Nitrogen was not intentionally introduced into the argon in this experiment and probably was present through faulty handling of the gas. Its presence was indicated by the appearance of the nitrogen band spectrum in the positive column of a glow discharge operated between two electrodes in the tube. The fact that the argon metastables were destroyed in a very short time was established by studying the decay of argon metastables by a light absorption experiment.[18]

In spite of all efforts at purifying the argon, the y intercept of the $1/\tau_1$ *vs* π^2/X^2 plots was finite; in other words the constant G is finite, indicating a measurable volume loss of metastables. This observation agrees with the findings of the light absorption experiments, and so we believe that our measured values of G cannot for the most part be ascribed to impurities, but instead they represent a measurement of the instability of metastables under impact with neutral atoms.[19] The accuracy of measurement of G in these experiments was not great, but up to a few millimeters of pressure G appeared to increase linearly with pressure and for higher pressures more rapidly. At one millimeter, G for argon metastables was found to be 80 sec^{-1}. If we assume a collision diameter for normal argon atoms of 3.2A and utilize the r_m/r_n ratio given above, we can compute a collision frequency between metastables and normal atoms at one millimeter and 25°C of 1.6×10^7 sec^{-1}. Thus, a value of $G=80$ sec^{-1} corresponds to the argon metastables having a lifetime of 2×10^5 impacts with normal atoms at room temperature.

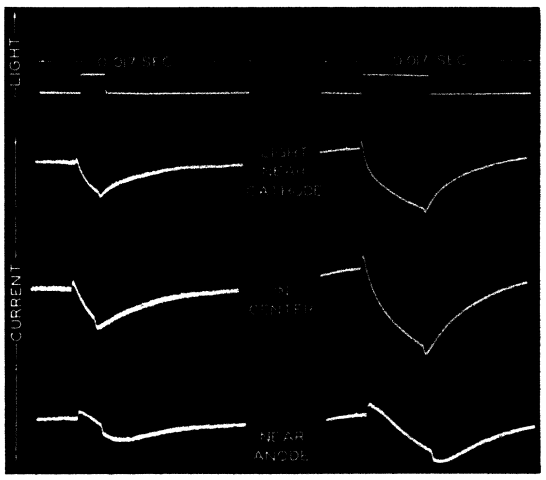

FIG. 5. Oscillograms of the current in a Townsend discharge with the primary stimulating light on steadily and light from a pulsed argon discharge directed across the gap between the electrodes. The left-hand group of traces were taken with the pulsed light 0.002 second in duration, the right group for the light 0.004 second in duration. These traces represent only small variations in a large dc current. Trace *h* in Fig. 6 illustrates a similar pattern obtained with a higher intensity of illumination.

V. CONVERSION OF METASTABLES INTO RADIATING ATOMS BY LIGHT RADIATION

The conversion of metastables to radiating atoms by light radiation is a well-known phenomenon. Penning[20] used this method in breakdown studies to reduce the number of neon metastables in tubes filled with neon and small admixtures of argon and thereby reduce the number of argon atom ionizations by collisions of the second kind. In our work this conversion process was utilized to measure the relative amount of electron emission produced by a metastable drifting to the cathode compared with that produced by a photon of the same energy striking the surface.

[18] This experiment is similar to those of Meissner and others in which the presence of metastables in a volume of gas is detected by their absorption of appropriate lines of the argon spectrum arising from transitions between the $3p^54s$ and $3p^54p$ configurations. As a separate project we have studied metastable lifetimes with this method also and will report our findings in a separate paper.

[19] We can rule out impacts between metastables and electrons, ions, or other excited atoms as a cause of this effect, because then the observed time constant would be dependent on the magnitude of the current, which is not observed except at currents above 10^{-7} amp (see Fig. 8).

[20] F. M. Penning, Z. Physik **57**, 723 (1929).

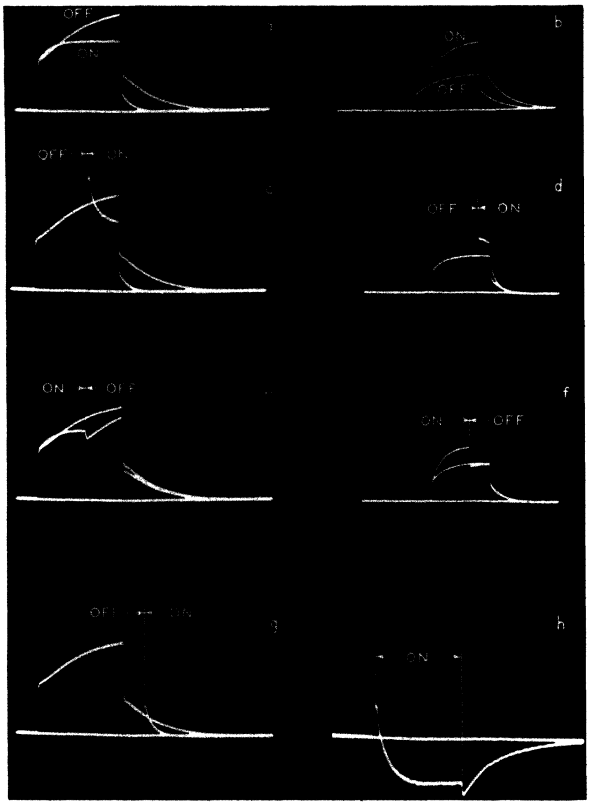

FIG. 6. Oscillograms of the current in a pulsed Townsend discharge with the side light on during alternate cycles of the primary light, except in *h*, for which the primary light was on continuously. The traces, *a*, *c*, *e*, *g*, and *h* were taken with a tantalum cathode for which $\gamma_r/\gamma_m=40$ percent. The traces *b*, *d*, and *f* were taken with a nickel cathode for which $\gamma_r>\gamma_m$. Note in traces *a* and *e* that with the side light on, the slow component rises at first more rapidly than when the side light is off. This effect is caused by the finite diffusion time required for the metastables to traverse the distance from $x=x_0$ (where they are first formed) to $x=0$ (the cathode) in the latter case, in contrast to the rapid flow of the energy in the form of photons in the former case.

Spectroscopically, the energy levels involved are as follows. The first excited configuration in argon is the $3p^54s$, which gives rise to four states, $^1P_1$, (radiating) $^3P_0$, metastable $^3P_1$ (radiating), and $^3P_2$ (metastable). If now light from an external argon discharge shines on the space between the electrodes, then those lines corresponding to transitions between the configurations $3p^54p$ and $3p^54s$ can be absorbed by atoms which are in states of the $3p^54s$ configuration. In general, only atoms in the two metastable states will be present in an appreciable density. On absorption of this radiation, the metastables are raised to various states in the $3p^54p$ configuration, from which they may decay downward either by going back to one of the metastable or one of the radiating states. In the former case, there will be no net effect on the density of metsastables. In the latter case, the atom will very soon decay to the ground state by radiating a photon. Thus, it is seen that effect of the light radiation is to convert some of the energy stored in the metastables into radiant energy. The four states of the $3p^54s$ configuration have energies differing at most by 0.29 ev (out of about 11.5 ev) so that the photon energies are very nearly the same as that of the metastables.

Our experiments were conducted with two arrangements. In the first the external light from a line source was focused so as to go through a small region between the electrodes near the anode, in the middle or near the cathode. In the second arrangement a ring-shaped discharge tube surrounding the Townsend tube was employed with which a much larger conversion factor was possible, but the light could not then be concentrated in any particular region.

In the first arrangement the most interesting results were obtained when the primary stimulating light for the Townsend discharge was maintained steady and the side illumination was pulsed. Typical oscillograms of the current through the Townsend tube are shown in Fig. 5. The current is seen to increase immediately on the application of the side light and then decrease slowly. When the side light is cut off, the current drop suddenly and then returns slowly to its steady-state value. The slow decrease and slow recovery is seen to start more rapidly when the sidelight crosses the gap near the cathode than when it crosses near the anode.

The interpretation of these patterns is as follows. The sidelight has two effects, that of increasing the number of photons striking the cathode and that of decreasing the metastable density in the region through which the light is passing. The sudden increase in currents when the light goes on is caused by the increase in the number of high energy photons striking the cathode. The slow decrease is caused by the diminution of the number of metastables available to diffuse to the cathode. Furthermore, the time for this diminution to "diffuse" to the cathode is longer when the light crosses the gap near the anode than when it crosses near the cathode; hence, the slow decrease occurs with a time lag when the light crosses near the anode. Finally, the net reduction in current through the tube with the side light on shows that in this case the photons are less effective than the metastables in producing electron emission at the cathode.

In the second arrangement a light source was used consisting of a piece of $\frac{3}{4}$-in. glass tubing bent into a circular shape to fit around the Townsend tubes of the second type. Electrostatic effects produced by noisy discharge conditions made it necessary to interpose grounded copper screening between the light source and the Townsend tube. This probably reduced the available light by at least 75 percent. The outer side of the discharge tube was aluminized to increase the light going in the inward direction. With this arrangement oscillograms were obtained as shown in Fig. 6.

The light source was pulsed at a frequency of 15 cps (as compared with 30 csp for the stimulating light), so as to permit direct comparison of the patterns with and without the side light. In the top two patterns (*a* and *b*),

oscillograms are shown for the case in which the side light was turned on before the stimulating light, and kept on during the entire cycle. In oscillogram *a* the effect of the light was to decrease the amplitude and the fundamental time constant, τ_1, of the slow component. In *b* the effect was the opposite, although the change in τ_1 is less evident, since the increased regeneration brought about by the increased value of i_s increases T_1 and masks the actual decrease in τ_1. The other oscillograms in Fig. 6 illustrate cases in which the side light was either turned on or turned off during the time the normal current pattern was visible.

For nearly every case studied the net effect of the side light was to reduce the magnitude of the slow component. Patterns *b*, *d*, and *f* in Fig. 6 illustrates the opposite case. They were obtained with nickel surface in an unknown state of contamination, a situation we did not observe in later work. The oscillograms are shown here only because they illustrate clearly the effect γ_r being greater than γ_m, when this is the case.

In order to obtain quantitative information from these patterns, we apply a first-term analysis similar to that described in I. First, the time constant of the slow component was measured with and without the side light on, and from these data, τ_1 computed for the two cases. Now, as indicated in Eq. (6), π^2D_m/X^2 includes the contribution of diffusion losses to $1/\tau_1$ and G the effect of volume destruction. For the side light off G includes only the normal volume loss due to collisions between metastables and normal argon atoms, G_c. With the side light on G includes, in addition, the volume loss caused by the side light, G_s. Thus, the difference between $1/\tau_1$ with and without the side light is a measure of G_s. With our light source the maximum value we could obtain for G_s was about 1500 sec^{-1}.

If one is concerned only with those metastables described by the first-term of the fourier analysis of the initial distribution, then the quantities (π^2D_m/X^2), G_c, and G_s are also a measure of the rate at which the metastables are destroyed at the electrodes, in the gas by collision, and in the gas by the side light. Furthermore, since we are dealing with the first term, exactly one-half of the electrode destruction will be at the cathode and one-half of the photons released in either type of volume destruction will go to the cathode. Thus, the quantities

$$\frac{\pi^2D_m/2X^2}{(\pi^2D_m/X^2)+G_c} \quad \text{and} \quad \frac{G_c/2}{(\pi^2D_m/X^2)+G_c}$$

represent the fractions of the excitation energy in the metastables which without side light reach the cathode by metastables and by photons, respectively. Immediately after the side light is turned on, the rate of arrival of metastables remains unchanged, but the rate of arrival of photons increases suddenly by the factor $(G_c+G_s)/G_c$. Then, gradually, a new steady-state is set up, for which the fractional carriers of energy are given by expressions above, except that G_c is replaced by G_c+G_s.

The measurement of γ_r/γ_m can be made using the amplitude of the slow component either immediately after the light is turned on or using the value of this component after the new equilibrium has been attained. We have found the former method better. A pattern of the type shown in trace *g* in Fig. 6 is used. The quantities π^2D_m/X^2, G_c, and G_s, are established from time constant studies. Then the magnitude of the slow component just before the side light is turned on, s, and its value just afterwards, $s+\Delta s$, is measured. Both s and $s+\Delta s$ will be directly proportional to the electron currents leaving the cathode due to the combination of metastables and photons from converted metastables striking the cathode, i.e.,

$$\Delta s/s=\gamma_rG_s/\gamma_m(\pi^2D_m/X^2)+\gamma_rG_c,$$

so that

$$\gamma_r/\gamma_m=(\Delta s/s)(\pi^2D_m/X^2)/[G_s-(\Delta s/s)(G_c)]. \tag{8}$$

In this equation all quantities on the right-hand side are measurable, so that γ_r/γ_m can be evaluated directly. In case the normal volume loss, as measured by G_c, is caused by impurities which do not yield photoelectrically active photons, then the second part of the denominator should be omitted.

The accuracy of measurement of the various quantities involved was not great, probably ±20 percent, mainly because of the presence of the electrical noise induced in the Townsend current by the operation of the discharge tube in close proximity. Nevertheless, a large difference between the γ_r/γ_m ratio for the tantalum cathode as compared with those of molybdenum and BaO cathodes was clearly discernible. The average value of γ_r/γ_m as determined by this method was 0.40 for tantalum, 0.08 for molybdenum, and 0.10 for barium oxide.

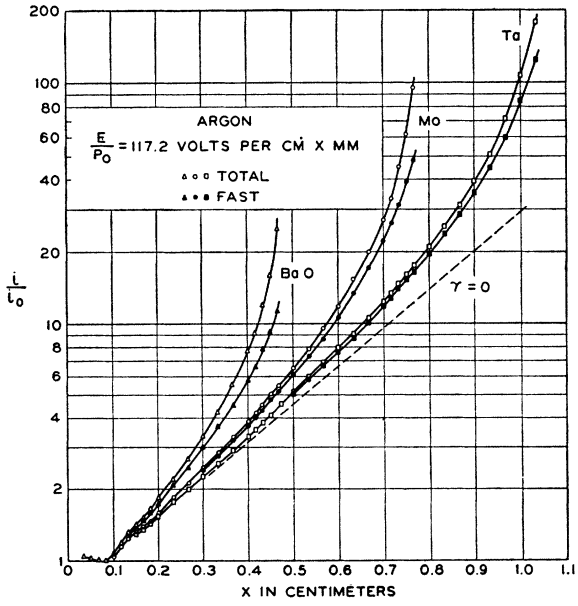

FIG. 7. Townsend plots of i/i_0 *vs* X for three cathode materials in argon at $E/p_0=117.2$ volts/cm×mm taken with $p_0=1.535$ mm.

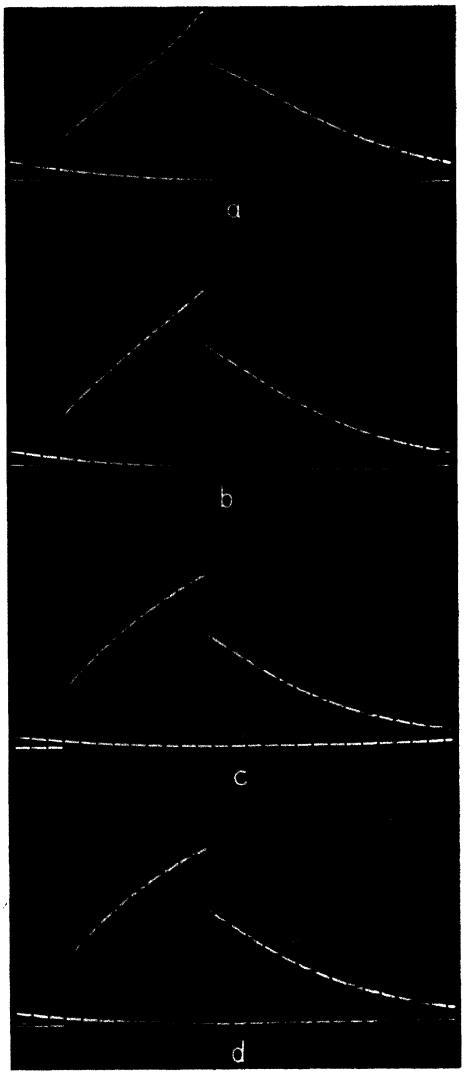

FIG. 8. Oscillograms of the current in a pulsed Townsend discharge for various intensities of the stimulating light, the applied voltage and electrode separation being maintained constant. The amplifier gain was adjusted to give the same maximum vertical deflection in each case. In *a* the maximum current value $=5\times10^{-7}$ amp, in *b*, one-half, in *c*, one-fourth, and in *d*, one thirty-second that amount. The pattern is seen to be the same for both *c* and *d*, while in *b*, and more so in *a*, the trace exhibits a positive curvature. If the light is left on continuously in case *a*, breakdown will ensue. While we did not examine closely the variation of the distortion with current, it appeared as if it was never present in serious amounts for currents less than 10^{-7} amp.

VI. TOWNSEND RUNS

In making a Townsend run the amplitudes and time constants of the fast and slow components were measured for 20 to 50 values of X. Typical plots of the fast component and total current are shown in Fig. 7. In such runs any variations in the intensity of the light source was effectively canceled out by the null method of measurement. Time variations in the photoemission sensitivity of the cathode in either the Townsend tube or the vacuum phototube could, however, introduce errors. We tried to minimize such errors by allowing the apparatus to "warm up" for several hours before starting a run and then periodically repeating complete runs to check the reproducibility of the data. For values of i/i_0 less than about ten, the measurements were in general reproducible to better than 1 percent. At higher ratios the accuracy of setting of the electrode spacings, and possibly slight variations in γ, made the variations larger. In general, if the gap had been allowed to break down between runs, there would be a noticeable change in the i/i_0 values.

We have labeled the distortions at high currents as being caused by space charge, although we have no direct proof that this is the cause. The oscillograms in Fig. 8 illustrate current forms for several values of the current as indicated in the caption. The distortion appeared to be of the kind which would make the slow component larger than expected by an exponential form at high currents.

The Townsend curves shown in Fig. 7 illustrate the back diffusion loss of electrons at applied voltages below 12 volts. They also exhibit a wave-like form for applied voltages below about 70 volts, caused by the lack of a constant value of α_i. Both of these effects have been discussed by the Eindhoven-Phillips workers.[6] We used for our value of i_0 the minimum value of the current which was normally observed for applied voltages in the range 12 to 15 volts. The value of x_0 was established by drawing a smooth tangent to the data for the fast component of current on the low γ-surface and taking the value of X where this line intersected the current value of i_0.

The best value of α_i corresponding to a set of data for a particular E/p_0 value was determined by a trial-and-

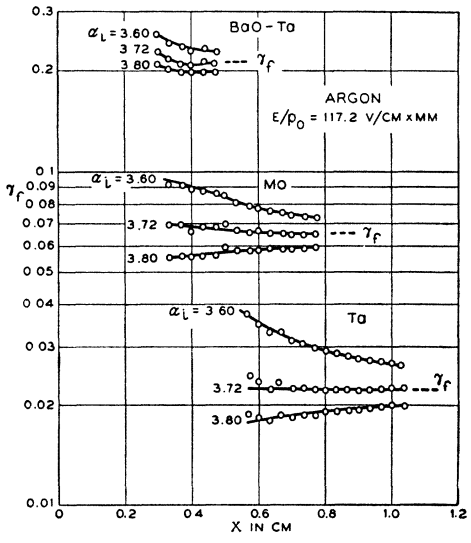

FIG. 9. Values of γ_f computed from i_f/i_0 data for three assumed values of α_i. Here the value of $\alpha_i=3.72$ cm^{-1} and the value of γ_f indicated by the dashed line was taken as the "best" fit of these parameters in the Townsend equation to the experimental data.

error method. A value of α_i was assumed, and then, measured values of i_f/i_0 being taken, γ_f-values were computed, using the Townsend equation. For the "best" value of α_i these γ_f-values should not vary with X. In Fig. 9 such computed values of γ_f are plotted *vs* X for three assumed values of α_i, of which the middle one was taken as "best." Note the sensitivity of the resultant γ-values to relatively small differences in the α_i-values.

The values of γ and γ_f were computed from i/i_0 and i_f/i_0 data. The value of γ_s, obtained by subtracting γ_f from γ, in general decreased with increasing X especially for lower values of E/p_0, for which the fraction of metastables destroyed in the gas is larger (see Fig. 10). The main cause of the decrease is the increasing fraction of the metastables which are lost in the volume of the gas as the electrode spacing is made larger coupled with the fact that the photons emitted in this process are usually less effective in causing electron emission at the cathode than the metastables (i.e., $\gamma_r<\gamma_m$).

In an attempt to take into account the varying fractions of metastables diffusing to the cathode and being lost in the volume, we applied the so-called first-term analysis described in I. In this analysis it is shown [Eq. (35)] that

$$f_{esc}\left[\alpha_m\gamma_m+\alpha_m\gamma_r\left(\frac{GX^2}{\pi^2D_m}\right)\right] = \alpha_i\frac{i_0i_{s1}}{i_f(i_{s1}+i_f)}\left[1+\frac{GX^2}{\pi^2D_m}\right]H, \quad (9)$$

where H is a function of α_iX and α_ix_0 as defined by Eq. (36) in I. Thus, if the right-hand side of this equation is plotted as a function of $(GX^2)/(\pi^2D_m)$, then there should result a straight line having a slope $\alpha_m\gamma_rf_{esc}$ and a y intercept of $\alpha_m\gamma_mf_{esc}$. A typical plot is shown in Fig. 11. This method of analysis seems about as satisfactory as any for evaluating $\alpha_m\gamma_m$, but for obtaining $\alpha_m\gamma_m$ the light destruction scheme, described in Sec. V is probably better.

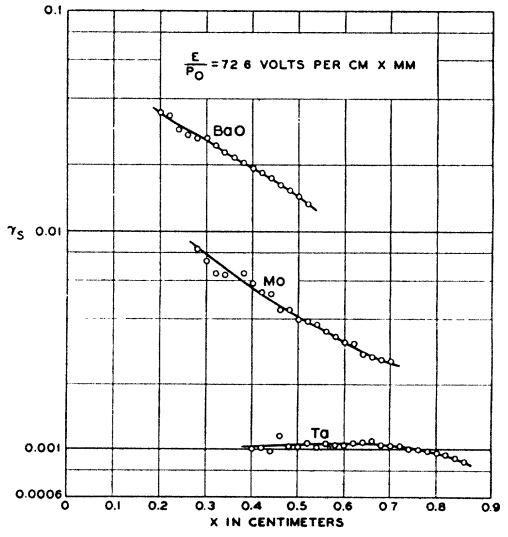

FIG. 10. γ_s and a function of X for three cathodes.

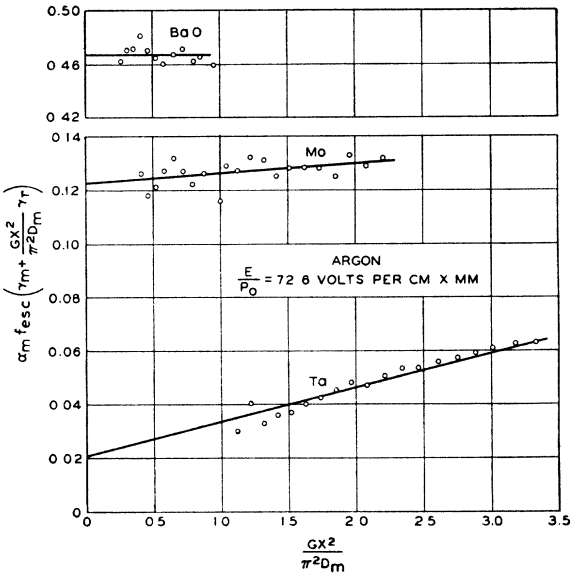

FIG. 11. Plots for three cathode materials showing application of "first-term" analysis of slow component for determining $\alpha_m\gamma_m$ and $\alpha_m\gamma_r$.

The quantity f_{esc} in the expression for γ was evaluated by making detailed measurements of the current in the Townsend tube at low voltages. Such data are shown in Fig. 12. We assumed that the current of elec-

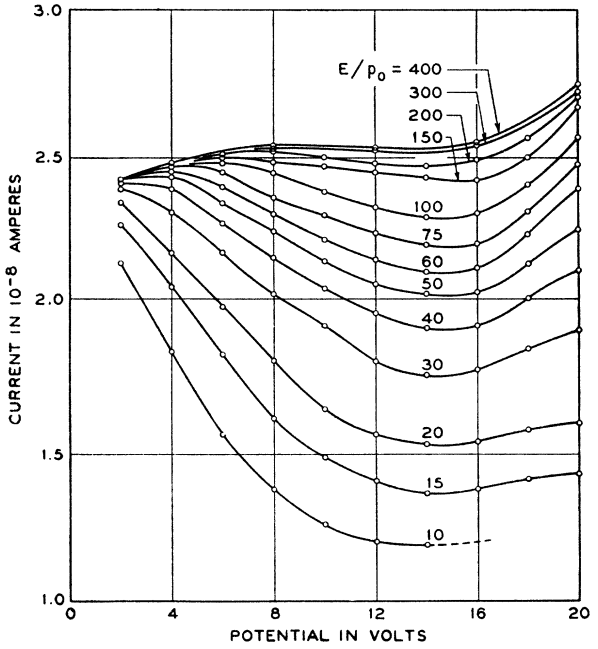

FIG. 12. "Low-voltage" Townsend plots obtained with a molybdenum cathode and argon gas with $p_0=1.535$ mm and E/p_0 varied by changing E only.

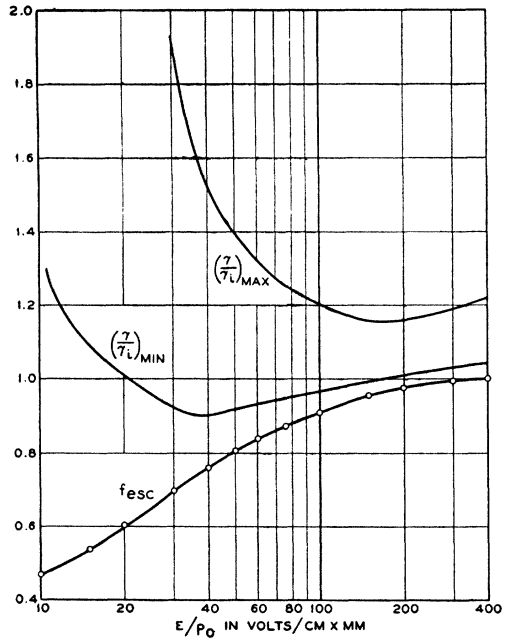

FIG. 13. f_{esc} as obtained from the 14-volt values of current in Fig. 11, and values of γ/γ_i as calculated by Eq. (11) for the extreme cases of no volume destruction and complete volume destruction of metastables along with other assumptions given in the text.

trons liberated from the cathode was given by 2.56×10^{-8} amp, the value observed for the $E/p_0=400$ curve in the region of 8 to 14 volts. The fall-off at six volts and below for the higher E/p_0 curves was due, we believe, to the influence of the size of the holes in the anode compared with the electrode spacing. The fraction of the liberated current which is observed at 14 volts is plotted *vs* E/p_0 in Fig. 13. This fraction we assume to be a measure of f_{esc}. It was found to be independent of the cathode surface for the various cathodes

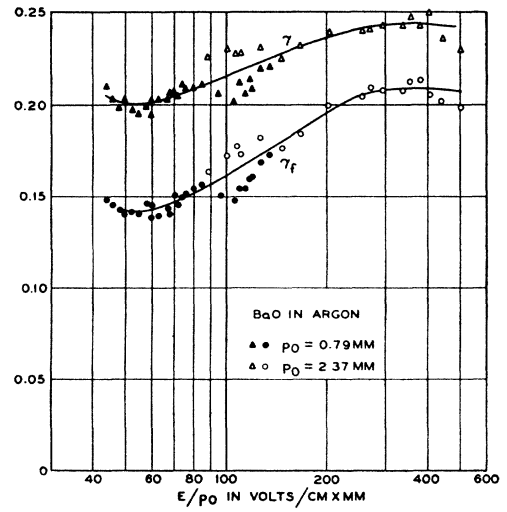

FIG. 14. γ and γ_f for a BaO-Ni surface using Eq. (10) and current amplification data obtained on a BaO-Ni surface and a pure Ni surface.

at our disposal, Ta, Mo, and BaO. (Crude measurements of the long wavelength photoelectric threshold indicated a work function of about 4.5 ev for the first two and 2.25 ev for the last.)

As indicated earlier we were unable in these studies to change the pressure in the tubes and retain the same efficiency of cathode emission. Thus, we were unable to obtain γ-measurements from complete Townsend runs as a function E/p_0, since at a given pressure complete runs for all surfaces could not be made over a range of E/p_0 greater than a factor of two. The data obtained from complete Townsend runs served mainly to establish the breakdown of γ into various parts.

The variation of γ_f with E/p_0 was obtained for the BaO surface, however, by comparing the ratios of i_f/i_0 of the BaO surface with that of a low γ-surface, in this case, nickel. (These measurements were made with the first type of tube.) Now, it can be readily shown that if $H=i/i_0$ for the high γ-surface ($\gamma=\gamma_H$) and $L=i/i_0$ for the low γ-surface ($\gamma=\gamma_L$), we have

$$(\gamma_H-\gamma_L)/(1-\gamma_L)=(H-L)/H(L-1). \qquad (10)$$

Although γ_L was not known percentagewise with great accuracy, its value was somewhere close to 0.02. On the other hand, γ_H had values between 0.15 and 0.20. Thus, a determination of γ_H by means of this relation could be made with reasonable accuracy, and without making a complete Townsend run. The γ-data as obtained by this method are shown in Fig. 14 for a BaO on Ni surface. Comparison of the curve of γ_f with that of f_{esc} in Fig. 13 suggests strongly that the variation of γ_f over a range of E/p_0 covered is caused mainly by the variation of f_{esc}.

This observation implies that the quantity $[\gamma_i+(\alpha_r/\alpha_i)f_{rk}\gamma_r]$ is constant over this range. Since α_r/α_i is certainly increasing for decreasing E/p_0, one must assume either that γ_i decreases with decreasing E/p_0, or that γ_i is constant and that the value of $[(\alpha_r/\alpha_i)f_{rk}\gamma_r]$ though increasing is still small compared with γ_i. We are inclined to favor the latter, first, because the data available of γ_i measurements by ion beam methods, though meager, show very little variation of γ_i with ion velocity in the low velocity range,[21] and, second, because the measured values of γ_r/γ_m for BaO as given in Sec. V are quite small, about 10 percent. At still lower values of E/p_0, the contribution of the radiation term will, of course, become much more important.

VII. GENERAL DISCUSSION

In Table II are listed values of the various factors making up γ. The methods by which f_{esc}, α_i, γ_f, γ_s, $\alpha_m\gamma_m$, and γ_r/γ_m were evaluated have been described in the preceding discussion. The quantities α_m and α_r could not be measured, and so we used the calculated

[21] Private communication of H. D. Hagstrum of these Laboratories. His studies now underway indicate that γ_i as measured by an ion beam method increases only very slowly in the range from 10 to 100 ev of ion energy for He^+ on a Mo target.

values of Kruithof,[6] who evaluated the ratio

$$N_r=(\alpha_m+\alpha_r)/\alpha_i$$

as a function of E/p_0 for the various rare gases. We further assumed that $\alpha_m=\alpha_r$, which seems to be a reasonable guess, lacking more detailed information on which to base an estimate.[22] The γ_m-values were then calculated from α_m calculated in this way and from the values of $\alpha_m\gamma_m$. Next, using the γ_r/γ_m data, γ_r was computed. Finally, $(\alpha_r/\alpha_i)f_{rk}\gamma_r$ was computed assuming $f_{rk}=0.4$. Then γ_i was evaluated from γ_f and f_{esc}.

Considering the accuracy of the original data and the many operations required on them, the values of γ_i, γ_m, and γ_r as listed can hardly be more accurate than 10 to 20 percent. Bearing in mind these limitations, we see that γ_m and γ_i have closely the same value, while, on the other hand, there is no such simple relationship between γ_r and γ_i or γ_m.[23]

The physics of electron emission caused by ion impact on surfaces has been discussed most recently by Cobas and Lamb.[24] They have investigated theoretically the process in which ions are assumed to be first neutralized by electrons being captured in excited states. The excited atom on closer approach to the surface then gives rise to the electron emitted into the gas. If the second process is the limiting one (i.e., assuming all electrons are captured in excited states),[25] then our observation of $\gamma_m\approx\gamma_i$ is not unreasonable.

The lack of any correlation between γ_r and γ_m or γ_i may be due to the fact the photoelectric process involved in these studies involve high energy photons. These photons enter the cathode probably to a depth of several atomic layers (volume photoelectric effect). The subsequent escape of the electron from the cathode depends on a variety of effects not all of which involve the detailed nature of the surface.

The variation of γ with E/p_0 has been shown to be dependent on a variety of factors which will depend on the conditions of the experiment. One can calculate, however, two limiting cases, namely, that in which all metastables are converted into radiating atoms by collisions and that in which none are so converted. We shall take $f_{rk}=f_{rk}'=0.4$,[26] and for the first case assume $f_{mk}=0$, $f_{mr}=1$, while for the second we shall take $f_{mk}=0.4$ and $f_{mr}=0$. Assuming, as before, $\alpha_m=\alpha_r=\frac{1}{2}N_r\alpha_i$, and that $\gamma_m=\gamma_i$, we have

$$\begin{aligned}&\gamma=f_{esc}\gamma_i(1+0.4N_r\gamma_r/\gamma_m)\text{ for the first case,}\\&\gamma=f_{esc}\gamma_i[1+0.2N_r(1+\gamma_r/\gamma_m)]\text{ for the second case.}\end{aligned}\tag{11}$$

The quantity γ/γ_i is plotted *vs* E/p_0 in Fig. 13 for these two cases assuming $\gamma_r/\gamma_m=0.1$, f_{esc} given by data in the plots in Fig. 12, and N_r by the calculations of Kruithof.[6] The actual observed values of γ will be somewhere between these limiting curves being closer to the higher value at high E/p_0 and vice versa at low E/p_0.

The literature contains numerous measurements of γ.[1–3] In view of dependence of γ on X which we mentioned earlier, it seems likely that some of these measurements may have been in error for not properly taking this effect into account. Nevertheless, the data for argon as summarized by Druyvesteyn and Penning[27] appear for the most part accountable in terms of the relation given above. It is also worth noting that γ-values given by Kruithof and Penning,[28] for the case of small argon admixtures in neon, which show a decrease in γ for very small values of E/p_0, may be explained by lack of a γ_r-contribution here if the neon atoms in the radiating (as well as in the metastable)

TABLE II. Data giving the various factors making up γ. The data for the two higher values of E/p_0 were obtained with $p_0=1.535$ mm and the surfaces in the same condition. The data for the lowest value of E/p_0 were obtained with $p_0=4.135$ mm and the surfaces having a reduced efficiency.

Gas-dependent factors:

E/p_0 volts/cm × mm	f_{esc}	α_i cm^{-1}	α_r, α_m cm^{-1}
195.4	0.97	6.63	2.6
117.2	0.91	3.72	2.4
72.6	0.86	5.10	7.0

Cathode-dependent factors:

$\frac{E}{p_0}$	Cathode	γ_f	γ_s near breakdown	$\alpha_m\gamma_m$	$\frac{\alpha_r}{\alpha_i}f_{rk}\gamma_r$	γ_i	γ_m	γ_r
195.4	Ta	0.026	0.0025	0.062	0.0014	0.026	0.023	0.009
195.4	Mo	0.076	0.0074	0.160	0.0008	0.071	0.060	0.005
195.4	BaO-Ta	0.23	0.050	0.83	0.005	0.23	0.31	0.031
117.2	Ta	0.022	0.0026	0.056	0.002	0.022	0.023	0.009
117.2	Mo	0.065	0.011	0.158	0.001	0.071	0.065	0.005
117.2	BaO-Ta	0.21	0.065	0.65	0.007	0.22	0.27	0.027
72.6	Ta	0.0060	0.0009	0.025	0.0017	0.0053	0.0035	0.0021*
72.6	Mo	0.030	0.0025	0.14	0.001	0.034	0.020	<0.001*
72.6	BaO-Ta	0.073	0.013	0.54	···	0.085	0.078	···

* No γ_r/γ_m-measurements were made by the light destruction method for the cathodes in this condition, so we use here the less reliable data obtained from the slopes of the curves in Fig. 11.

[22] From the data obtained in studies of the Penning effect, A. A. Kruithof and M. J. Druyvesteyn [Physica 4, 450 (1939)] calculated a value of $\alpha_m/(\alpha_m+\alpha_r)$ as high as 95 percent for some values of E/p_0. We believe this high value could have been caused by the ionization of argon atoms by neon atoms not only in the metastable states, but in the nearby radiative states also. The lifetime of the latter when enhanced by the phenomenon of the "imprisonment of resonance radiation" could well have been adequate in the conditions of their experiments to permit this process.

[23] If our assumption that $\alpha_r=\alpha_m$ is widely in error, then, obviously, the measurements do not give $\gamma_i\approx\gamma_r$, but merely that γ_i/γ_m is roughly constant for the cathodes we studied. This observation is still in contrast to the lack of such a fixed ratio between γ_m and γ_r.

[24] A. Cobas and W. E. Lamb, Phys. Rev. **65**, 327 (1944).

[25] Here, the excited states need not be metastable, because the time spent by the excited atom in the proximity of the surface is short compared to the lifetime of even radiative states.

[26] If it were not for the phenomenon of the imprisonment of resonance radiation, f_{rk} would be 0.5 for infinite plane-parallel geometry. Instead, the radiation flows in something like a diffusion process [see T. Holstein, Phys. Rev. **72**, 1212 (1947)]; hence, f_{rk} will be less than 0.5, though probably still greater than f_{mk} with $G=0$.

[27] See Fig. 20 in reference 2.

[28] A. A. Kruithof and F. M. Penning, Physica 4, 430 (1937).

states are destroyed in collisions of the second kind with argon atons. Thus, γ here would follow simply the f_{esc} curve.

It is unfortunate that we were unable to get good γ-data over a larger range of E/p_0. With the techniques developed by Penning[11] and his co-workers for producing stable, high γ-surfaces it may be possible to carry out such experiments.[29] Our tubes were not very suitable for this purpose because of the massive cathode we employed, the large gas volumes involved, and difficulties presented by the extended sputtering required by his techniques. It would also be desirable to obtain experimental values of α_m and α_r, which obviously play an important role in the interpretation of γ. Similarly, there is need for a clearer understanding of the physical process involved in the destruction of metastables by collisions in the gas, an effect which may be different in magnitude for the two metastable states.

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[29] The pressure changes could probably be made most easily by starting the measurements at high pressure, and then proceeding to lower pressures (and hence higher E/p_0's), letting the gas expand into evacuated glass bottles, by shattering "break-off" tips. In this way the gas purity would be unchanged during the pressure change.

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Range of High Energy Electrons in Aluminum

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An electron beam has been extracted from the 25-Mev betatron of the Physics Department of the University of Saskatchewan by using a magnetic peeler similar in design to that developed at the University of Illinois. The high energy electron beam was analyzed by bending it through an angle of 90° with a magnetic field. The high energy electrons were passed in turn through a flat ionization chamber, the aluminum absorber and a second ionization chamber. By measuring the ratio of the two ionization currents for different thicknesses of the absorber, the range of the electrons was determined. The ranges of electrons having energies from 12 to 16 Mev were obtained in this way and found to be in agreement with an empirical formula previously proposed by one of the authors (see reference 7 of this paper).

INTRODUCTION

EXPERIMENTAL determinations of the ranges of high energy electrons in the region above 3 Mev have been almost nonexistent until the recent measurements on nuclear beta-rays by Hereford[1] on B^{12} (13.4 Mev) and Alvarez[2] on N^{12} (16.6 Mev) and measurements by Hereford and Swann[3] on monoenergetic electrons. Short-lived nuclear activities having energies in this high energy region have been reported in the literature. The energies of these beta-rays are most readily determined by their range in aluminum. For this reason the authors felt that further investigations on the ranges of high energy electrons was justified. The ranges of monoenergetic electrons from the University of Saskatchewan betatron with energies from 12 to 16 Mev have been measured and are reported in this paper.

EXPERIMENTAL ARRANGEMENT

Electrons were removed from the betatron using a magnetic shunt peeler device very similar to that developed by Skaggs *et al.*[4] The electron beam was passed through a 1-cm aperture one meter from the betatron and was deflected through 90° in a magnetic field as indicated in Fig. 1. After passing through an aluminum ionization chamber, 5 cm in diameter and 6 mm thick, the electrons pass through an absorber of aluminum as indicated, and through a second ionization chamber of the same diameter as the first but five times the thickness. The central electrodes of both ionization chambers were connected through shielded cables to a detecting device in the control room of the betatron. The details of this device are shown in Fig. 2. The central electrode and the outer walls of the chambers were made of aluminum 0.001 in. thick. A voltage of

[1] F. L. Hereford, Phys. Rev. **74**, 574 (1948).
[2] L. W. Alvarez, Phys. Rev. **75**, 1815 (1949).
[3] F. L. Hereford and C. P. Swann, Phys. Rev. **78**, 727 (1950).

[4] Skaggs, Almy, Kerst, and Lanzl, Phys. Rev. **70**, 95 (1946). The porcelain electron doughnut was obtained through the courtesy of D. W. Kerst.

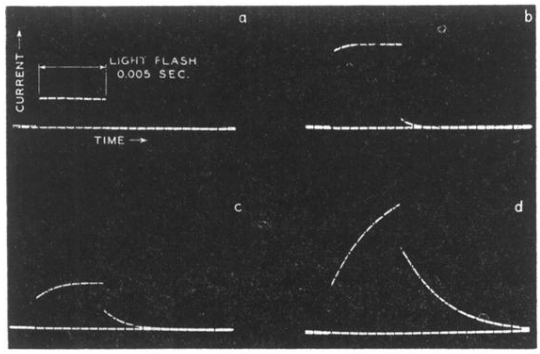

FIG. 2. Typical oscillograms of the current in a Townsend discharge with pulse light stimulation. The traces were taken with a fixed electrode separation and increasing values of applied voltage going from *a* to *d*. The amplifier gain was reduced 5× for traces *c* and *d*. Trace *a* corresponds to a current consisting entirely of photoelectrons released from the cathode by the stimulating light. The other traces show the effect of gas amplification and γ_f-processes by the increase of the in-phase component and the effect of the γ_s-processes by the appearance in successively larger amounts of a delayed component.

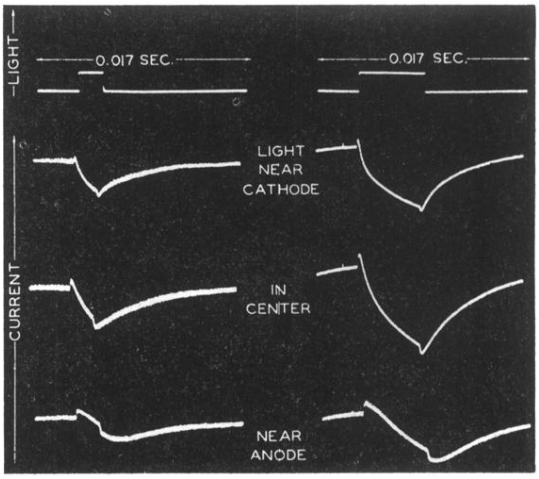

FIG. 5. Oscillograms of the current in a Townsend discharge with the primary stimulating light on steadily and light from a pulsed argon discharge directed across the gap between the electrodes. The left-hand group of traces were taken with the pulsed light 0.002 second in duration, the right group for the light 0.004 second in duration. These traces represent only small variations in a large dc current. Trace *h* in Fig. 6 illustrates a similar pattern obtained with a higher intensity of illumination.

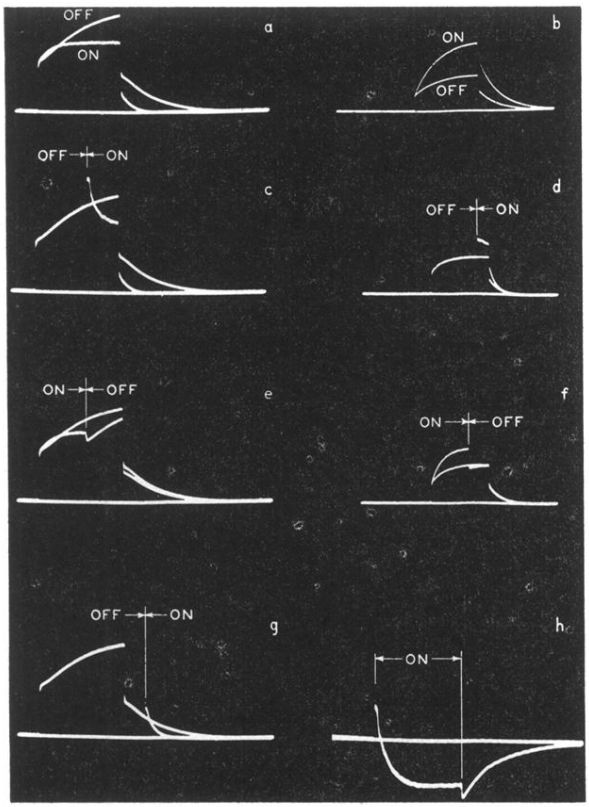

FIG. 6. Oscillograms of the current in a pulsed Townsend discharge with the side light on during alternate cycles of the primary light, except in *h*, for which the primary light was on continuously. The traces, *a*, *c*, *e*, *g*, and *h* were taken with a tantalum cathode for which $\gamma_r/\gamma_m = 40$ percent. The traces *b*, *d*, and *f* were taken with a nickel cathode for which $\gamma_r > \gamma_m$. Note in traces *a* and *e* that with the side light on, the slow component rises at first more rapidly than when the side light is off. This effect is caused by the finite diffusion time required for the metastables to traverse the distance from $x = x_0$ (where they are first formed) to $x = 0$ (the cathode) in the latter case, in contrast to the rapid flow of the energy in the form of photons in the former case.

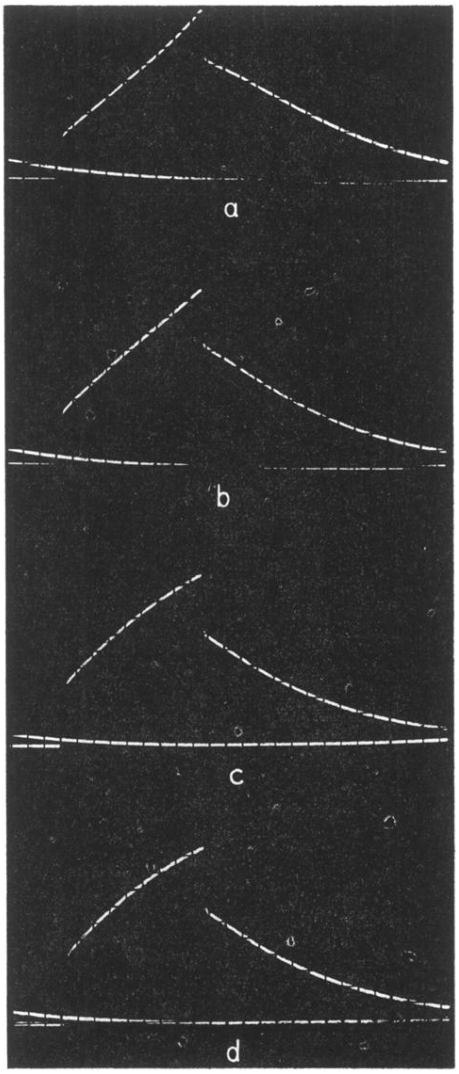

FIG. 8. Oscillograms of the current in a pulsed Townsend discharge for various intensities of the stimulating light, the applied voltage and electrode separation being maintained constant. The amplifier gain was adjusted to give the same maximum vertical deflection in each case. In *a* the maximum current value $=5\times10^{-7}$ amp, in *b*, one-half, in *c*, one-fourth, and in *d*, one thirty-second that amount. The pattern is seen to be the same for both *c* and *d*, while in *b*, and more so in *a*, the trace exhibits a positive curvature. If the light is left on continuously in case *a*, breakdown will ensue. While we did not examine closely the variation of the distortion with current, it appeared as if it was never present in serious amounts for currents less than 10^{-7} amp.