SECONDARY IONIZATION MECHANISMS IN AN $E \times B$ DISCHARGE IN HYDROGEN

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Abstract

A study of the secondary ionization mechanisms operative in an $E \times B$ Townsend discharge in hydrogen has been made by investigating the formative time lag to electrical breakdown in such discharges. Comparison of the experimental data with predictions from a theoretical model enables the secondary mechanisms to be distinguished and their separate contributions to be estimated. The results so obtained are compared with those derived from the equivalent pressure concept.

I. INTRODUCTION

The behaviour of a low energy electron swarm moving through a neutral gas in the presence of both electric and magnetic fields has been extensively investigated by Blevin and Haydon (1958), Haydon and Robertson (1963), and Fletcher and Haydon (1966). The results of these studies have supported the "equivalent pressure concept", which is that in the presence of crossed electric and magnetic fields the electrons behave energetically as they would if only the electric field were present and the neutral gas number density were increased from N to some equivalent value $N_{\text{eff}} \equiv [N]$ (where square brackets are used hereafter to denote effective values of the enclosed parameters). For the present work in hydrogen, $N = 3{\cdot}53 \times 10^{16} p_0$, with p_0 the gas pressure in torr at 0°C.

The equivalent pressure concept is based upon the assumption that the electron energy distribution function $F(\varepsilon, E/N, B/N)$ of the swarm in the $E \times B$ field is the same as the function $F(\varepsilon, [E/N])$ at the equivalent pressure in the absence of the magnetic field, the parameters E/N and B/N defining the swarm energy. The mechanisms shown to be important in a hydrogen discharge in an electric field only are the primary electron–gas molecule ionizing collision (the α process), photon impact on the cathode (the δ/α process), and positive ion impact on the cathode (the γ process). In a d.c. investigation of a discharge, the effect of the α process is obtained as the first ionization coefficient α/N, but the second and third processes cannot be separately distinguished and are measured together as the generalized secondary coefficient ω/α. Since the equivalent pressure concept is only applicable to electron mechanisms and thus not to the γ process, unless the relative contributions from the δ/α and γ processes are known when $B/N = 0$, the concept cannot be used to predict the variation of ω/α with B/N.

In recent years the accepted idea that the same mechanisms operate in an $E \times B$ discharge as in an E discharge has been questioned by Wasa and Hayakawa (1966) and Rasmussen *et al.* (1969). Both these groups have suggested that in an $E \times B$ discharge

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the electron energy may be much too low to result in ionization by the α process, and that the bulk of the ionization is due to the impact of positive ions with gas molecules (the β process). Since this latter process is a secondary mechanism it lends itself to investigation, along with the δ/α and the γ processes, by a study of the time lag τ for formation of a discharge after the application of a voltage greater than that required to cause breakdown of the gap. The time lag consists of two parts: the statistical lag τ_s, which is just the time required for initiating electrons to appear in the gap, and the formative lag τ_f, which is the time over which the discharge builds up to electrical breakdown. If a steady supply of initiating electrons is provided in the gap so that τ_s is made negligible, the formative time lag can then be studied to yield information about the secondary mechanisms acting in the discharge.

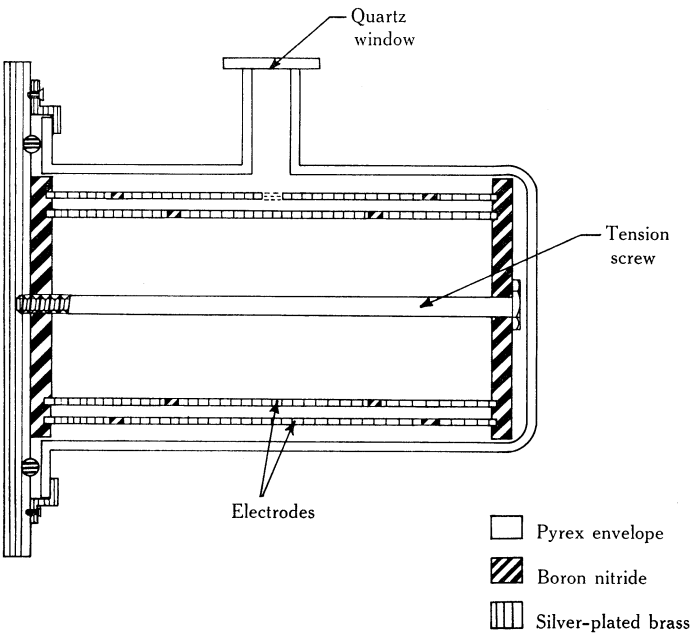

Fig. 1.—Schematic diagram of the ionization chamber.

Throughout the present work it has been assumed that the values of B/N used are sufficiently small for the recapture coefficient for electrons at the cathode to be considered constant and hence to have no effect on the observed trends.

II. Apparatus and Procedure

The experimental ionization chamber employed a cylindrical electrode assembly in order to overcome the problem of electron loss from the discharge by lateral drift in the $E \times B$ field. The chamber, which is shown in Figure 1, consisted of two concentric brass cylinders of thickness 0·2 cm, each divided by boron nitride rings into a central section with guard ring cylinders at either end. A 0·1 cm interelectrode spacing was used which, with an outer cylinder (anode) internal diameter of 3·0 cm,

produced a maximum electric field nonuniformity across the gap of 6%. The complete electrode assembly was positioned between two boron nitride end plates and tensioned by means of a screw along the axis of the electrode assembly. A series of fine holes in the centre of the anode allowed ultraviolet radiation to be directed onto the cathode. The ultraviolet light, which produced an initial steady current I_0 of order 10^{-12} A, was provided by a penray quartz lamp. The chamber was enclosed in a Pyrex glass bell jar envelope with side arms that allowed for evacuation and gas inlet and for a quartz window, aligned with the holes in the anode, to admit the ultraviolet radiation. The envelope was seated on a Viton O ring at a brass end plate and was sealed by means of a split-ring assembly tightened to the lip of the envelope by eight screws symmetrically distributed around the seal. Electrical connections to all six electrodes were brought out through the envelope by means of tungsten seals in the glass. In order to reduce outgassing and to present a reproducible surface to the discharge, all metal parts within the vacuum envelope were silver plated.

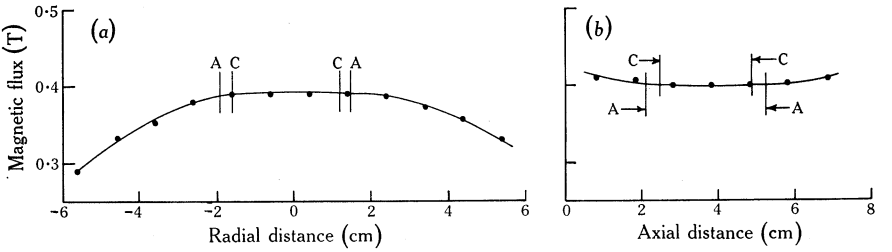

Fig. 2.—Scans of the magnetic field across the gap (*a*) radially at the mid-pole position and (*b*) axially along the central axis. The indicated positions of the anode A and cathode C show the interelectrode working volume.

The chamber was suspended between the poles of an electromagnet, the pole faces being 10 cm in diameter, with the magnetic field vector directed axially through the chamber. A continuously variable 0–15 A input to the electromagnet enabled magnetic fields in the range 0–0·5 T to be produced across the 7·5 cm pole gap. A Bell model 640 incremental Gaussmeter was used to measure the magnetic field. Figures 2(*a*) and 2(*b*) show the results of two scans across the working volume: (*a*) radially at the mid-pole gap position and (*b*) axially across the gap along the central axis of the pole faces. From the position of the gap as indicated on the figures, it can be seen that the variation of magnetic field within the discharge volume was less than $\pm 1\%$.

The ionization chamber was evacuated to a base pressure of 10^{-6} torr by means of a water-cooled oil diffusion pump and a two-stage rotary backing pump. Cylinder hydrogen was admitted to the system through a heated palladium–silver alloy osmosis tube and a needle valve. Gas pressure measurements were made to an accuracy of $\pm 1\%$ using an N.R.C. Alphatron model 820 gauge which was calibrated *in situ* against an M.K.S. Series 90 Baratron.

Before any measurements were taken, and between all sets of subsequent measurements, the electrodes were conditioned by means of a 50 mA glow discharge established in the electrode gap for several hours. The system was repeatedly flushed with purified hydrogen gas to help remove background contaminants.

The pulsed radial electric field was produced by a negative-going voltage pulse applied to the cathode, with the anode earthed. This pulse was formed by an ignitron-fired 0·1 μF energy storage capacitor circuit which was in turn triggered by a subsidiary thyratron-fired circuit. The pulse so formed had a rise time of 150 ns and dropped to 95% of its initial value after 200 μs in the absence of electrical breakdown of the gap. The behaviour of this voltage pulse was studied by means of a Tektronix type P6103 high voltage probe into a Tektronix type 549 Storage oscilloscope with a type W high gain differential comparator plug-in unit.

The technique used to measure the formative time lag was to apply a pulsed potential difference to the plates of magnitude less than the breakdown potential. In this case the top of the pulse, displayed on the oscilloscope, was flat when observed over 100 μs. This potential difference was then increased in steps of 1 V until breakdown was observed as a collapse of the voltage pulse. The value of τ_f corresponding to each value of potential difference was measured approximately 20 times. It was observed that, for voltage pulses of 1 or 2 V above the breakdown potential, τ_f had a statistical variation with a spread of values of $<20\%$, while for larger voltage pulses there was little change in τ_f. The problem of the statistical variation was overcome by taking the minimum time lag as τ_f. In this way, graphs of τ_f as a function of potential difference across the plates were obtained, such curves all being of similar shape and tending to infinity at the breakdown potential V_s. A study of these curves thus gave the value of V_s and from this τ_f could be replotted against the percentage overvoltage ΔV, where

$$\Delta V = \{(V - V_s)/V_s\} \times 100, \tag{1}$$

V being the value of the applied voltage pulse. The oscilloscope display of the voltage pulse enabled not only each formative time lag to be measured with an error of less than $\pm 2\%$ but also the voltage pulse height at the cathode (the non-earth electrode) to be determined to within ± 1 V.

The equivalent circuit for the discharge gap at breakdown is a resistor in parallel with a capacitor, which in turn is in parallel with the oscilloscope probe. The total impedance of this arrangement is such that when the voltage pulse has collapsed by 1 V, which is the minimum observable collapse and the point at which τ_f is measured, a current of the order of 10^{-8} A is flowing through the ionization chamber. Hence 10^{-8} A is taken as the breakdown current, and since $I_0 \approx 10^{-12}$ A, the ratio of the electron current I_- to I_0 is of the order of 10^4.

The validity of the equivalent pressure concept has been demonstrated for the primary ionization coefficient (Haydon and Robertson 1963; Fletcher and Haydon 1966). The effective value $[E/N]$ of E/N is given by

$$[E/N] = (E/N)\{1 + (\omega^2/\nu^2)\}^{-\frac{1}{2}}, \tag{2}$$

where $\omega = eB/m$ is the electron cyclotron frequency and ν is the effective collision frequency. The value of α/N used in the present calculations at the operative values of E/N and B/N at breakdown was that corresponding to the effective E/N in the $B/N = 0$ situation, multiplied by the ratio of the effective number density to the actual number density (Fletcher and Haydon 1966), namely

$$(\alpha/N)_{E/N, B/N} = \{[N]/N\}(\alpha/N)_{[E/N]}. \tag{3}$$

The effective collision frequency used to calculate $[N]$ was that determined by Fletcher and Haydon. Calculations of the generalized secondary coefficient ω/α at breakdown could then be made using the Townsend breakdown criterion in the form

$$(\omega/\alpha)\{\exp((\alpha/N)_{E/N,B/N}\,Nd)-1\}=1, \tag{4}$$

where d is the interelectrode spacing and ω/α is the arithmetic sum of the coefficients for all contributing secondary processes:

$$\omega/\alpha = \gamma + \delta/\alpha + \ldots. \tag{5}$$

III. Results and Discussion

As noted in the Introduction, it is important in the measurement of formative time lags to keep the statistical lag negligibly small. This condition can be achieved by irradiating the cathode with ultraviolet light so as to produce a steady flow of photoelectrons into the discharge. In the present experiments, a minimum of 10 electrons μs^{-1} were released from the cathode so making $\tau_s \leqslant 10^{-7}$ s, that is, less than 10% of the smallest value of τ_f observed and very much less than 10% of the majority of the measurements.

Values of τ_f in hydrogen were measured for N in the range $7{\cdot}1\times10^{17} \leqslant N \leqslant 1{\cdot}42\times10^{18}$ cm^{-3} ($20 \leqslant p \leqslant 40$ torr) and $0 \leqslant B/N \leqslant 4{\cdot}25\times10^{-19}$ T cm^3 ($0 \leqslant B/p \leqslant 150$ G torr^{-1}). The resulting values of the breakdown electric field to number density ratio E_s/N were in the range $309 \leqslant E_s/N \leqslant 421$ Td* with the corresponding $[E/N]$ range being $245 \leqslant [E/N] \leqslant 421$ Td. The experimental points for the variation of τ_f as a function of ΔV at $N = 1{\cdot}06\times10^{18}$ cm^{-3} are plotted in Figure 3(*a*) for three values of B/N, while similar data obtained at the extremes of the density range investigated are shown in Figure 3(*b*).

In order to determine which secondary mechanisms were operative in the present experiment, the data in Figure 3 have been compared with the theory developed by Davidson (Dutton *et al.* 1953). The latter author showed that when positive ion and photon impacts at the cathode, expressed in terms of their coefficients γ and δ/α respectively, are the only significant secondary mechanisms then the ratio of the electron current I_- at the cathode to the initial photoelectric current I_0 is given by

$$\frac{I_-}{I_0} = \frac{1-\exp(\lambda\tau_f)}{1-(\omega/\alpha)(G+D)\{\exp(\alpha d)-1\}}, \tag{6}$$

where $G = \gamma/(\omega/\alpha)$, $D = (\delta/\alpha)/(\omega/\alpha)$, and λ is a constant describing the time rate of current growth. Davidson also showed that

$$1-\frac{(\omega/\alpha)\alpha G\{\exp(\phi x)-1\}}{\phi}-\frac{\alpha(\omega/\alpha)D}{\psi\{\exp(\psi x)-1\}}=0, \tag{7}$$

where

$$\phi = \alpha-\lambda/W, \qquad \psi = \alpha-\lambda/W_-, \qquad 1/W = 1/W_- - 1/W_+.$$

In these expressions, α is the primary ionization coefficient and W_- and W_+ are the electron and ion drift velocities respectively. The generalized secondary coefficient

* 1 townsend (Td) $= 10^{-17}$ V cm^2.

ω/α is obtained from the breakdown criterion (4) using the value of α/N applicable to the measured breakdown value of E_s/N. Hence, for any experimental situation λ may be obtained from equation (7) and substituted into the ratio (6) to give a value of τ_f for comparison with the experimental value. This has been done using the equivalent pressure concept to give W_- in $E \times B$ fields (Blevin and Haydon 1958),

$$W_{-(E/N,B/N)} = W_{-[E/N]}\{1+(\omega^2/\nu^2)\}^{-\frac{1}{2}}. \tag{8}$$

The electron drift velocities measured by Schlumbohm (1965) have been used to give $W_{-[E/N]}$. No data are available for the effect of transverse magnetic fields on positive

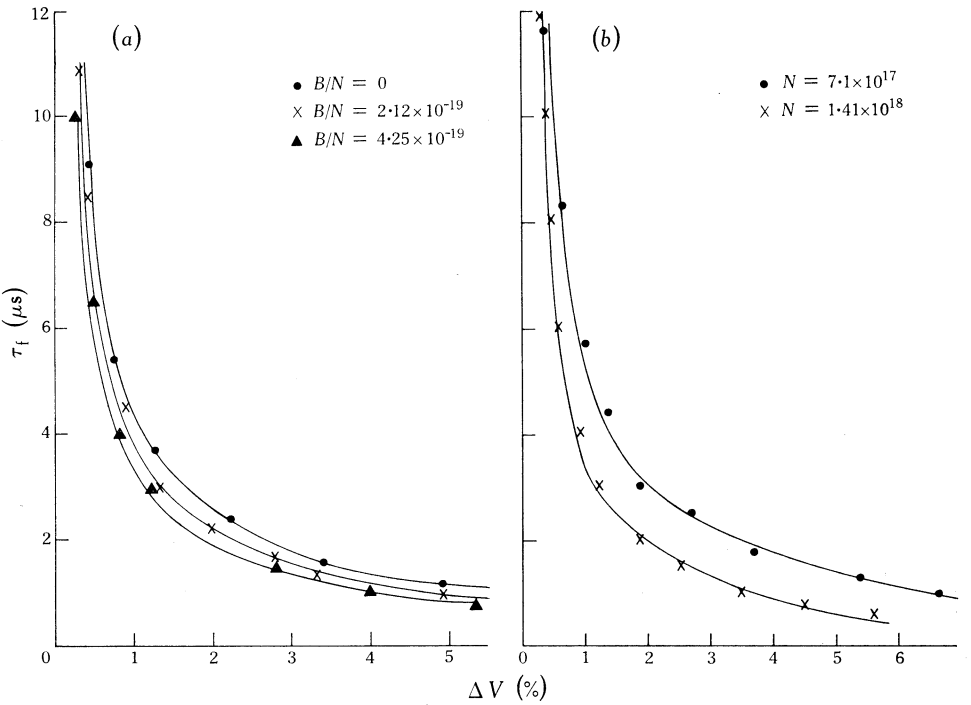

Fig. 3.—Formative time lag τ_f as a function of the percentage overvoltage ΔV. The theoretical curves are compared with experimental points (*a*) at $N = 1{\cdot}06 \times 10^{18}$ cm^{-3} and $E_s/N = 350$ Td for three values of B/N (T cm^3) and (*b*) at the extremes of the density range investigated: $N = 7{\cdot}1 \times 10^{17}$ cm^{-3} with $B/N = 0$ and $E_s/N = 421$ Td; $N = 1{\cdot}41 \times 10^{18}$ cm^{-3} with $B/N = 2{\cdot}83 \times 10^{-19}$ T cm^3 and $E_s/N = 310$ Td.

ion drift velocities but, since ω_+/ν_+ is very much less than unity for positive ions under the present conditions, we have made the approximation

$$W_{+(E/N,B/N)} \approx W_{+(E/N)} \tag{9}$$

and taken Schlumbohm's values of $W_{+(E/N)}$. The curves in Figure 3 show the predicted variations of τ_f with ΔV after optimization of the values of G and D to obtain a best

fit to the experimental points. It is evident that there is good agreement for the theory when based upon only positive ion and photon impact at the cathode.

The above analysis was used throughout the investigated range of E_s/N and B/N and in all cases values of G and D could be found which gave good agreement between theory and experiment. Data for the ratio D obtained in this way at $N = 1{\cdot}06 \times 10^{18}$ cm^{-3} and $E_s/N = 350 \pm 2$ Td were as follows.

B/N (10^{-19} T cm^3)	0	1·42	2·12	2·83	3·54	4·25
D	0·3	0·32	0·33	0·34	0·35	0·36

It is evident from equation (5) that this ratio must lie in the range $0 < D < 1$ and that $G = 1 - D$ if only these two mechanisms are operative.

An analysis of the variation of the breakdown potential V_s with the reduced magnetic field B/N is very complex problem. Dargan and Heylen (1968) have studied this dependence over a wide range of values of both E/N and B/N and have shown that for E/N near a critical value $(E/N)_k$, claimed by them to be 372 Td in hydrogen, the application of a moderate magnetic field has little effect on the sparking voltage. Indeed their Table 2 shows that, for an increase in B/N from zero to $2{\cdot}8 \times 10^{-19}$ T cm^3, V_s changes by only 0·5 V while a further doubling of B/N only causes an increase in V_s of 17 V. In the present work it was observed that, at $E_s/N = 350$ Td, variation of B/N from zero to $4{\cdot}25 \times 10^{-19}$ T cm^3 caused V_s to change by only ± 2 V, so enabling a single value of E_s/N to be assigned to the data for D tabulated above.

The generalized secondary coefficient in $E \times B$ fields has not been investigated nearly as much as the primary coefficient. In the present work the values of ω/α have been obtained from the breakdown potential of the gas, i.e. the voltage at which τ_f becomes infinite, using the Townsend breakdown criterion, equation (4). Knowing the contribution to ω/α from the δ/α process, it is possible to construct a family of curves of δ/α as a function of B/N, each at a fixed value of E_s/N. If the equivalent pressure concept is valid for the δ/α secondary mechanism, as suggested by Blevin and Haydon (1958), these data should be able to be related to $B/N = 0$ determinations of δ/α as a function of E/N obtained from experimental measurements of D and δ/α, such as those shown in Figure 4(*a*). A comparison is made in Figure 4(*b*) between the experimental results for δ/α as a function of B/N and the corresponding values calculated from the data of Figure 4(*a*) using the equivalent pressure concept (EPC) with an effective ratio $[v/N]$ of $7{\cdot}1 \times 10^{-8}$ cm^3 s^{-1} (Fletcher and Haydon 1966). The dashed portion of the EPC curve in Figure 4(*b*) has been obtained by backward extrapolation of the result in (*a*). As may be seen, the agreement between the predicted and experimental values is not good. It is well known that any comparison between different sets of data of secondary coefficients is unreliable because small changes in electrode surface conditions can greatly alter the magnitude of ω/α, and this effect is reflected in the divergence between the two sets of data at $B/N = 0$. Also, the values of ω/α within one set of data can differ by as much as $\pm 10\%$. The overall possible error in δ/α is estimated to be $\pm 15\%$, the additional uncertainties being $\pm 2\%$ in the values of W_- and no more than $\pm 3\%$ in the ratio D (since the accuracy of the fit to the curves of τ_f versus ΔV is very sensitive to the choices for G and D). Regardless of the magnitudes of the secondary coefficients, however, it is obvious from Figure 4(*b*) that the functional dependence of δ/α on B/N is very different in the two cases.

Now δ/α may be written as

$$\delta/\alpha = yg\theta/\alpha, \tag{10}$$

where y is the secondary electron yield from the cathode per incident photon, g is a geometrical factor that determines the probability of a photon reaching the cathode, and θ is the mean number of photons produced by an electron moving 1 cm in the direction of the electric field. Of these factors, y and g should be unchanged by the magnetic field so that δ/α is only dependent upon θ/α, the ratio of the excitation to the ionization coefficient. Since this ratio is determined by the electron energy distribution function $F(\varepsilon)$, the disagreement observed in Figure 4(*b*), indicates that $F(\varepsilon, B/N, E/N)$ is not the same as $F(\varepsilon, [E/N])$.

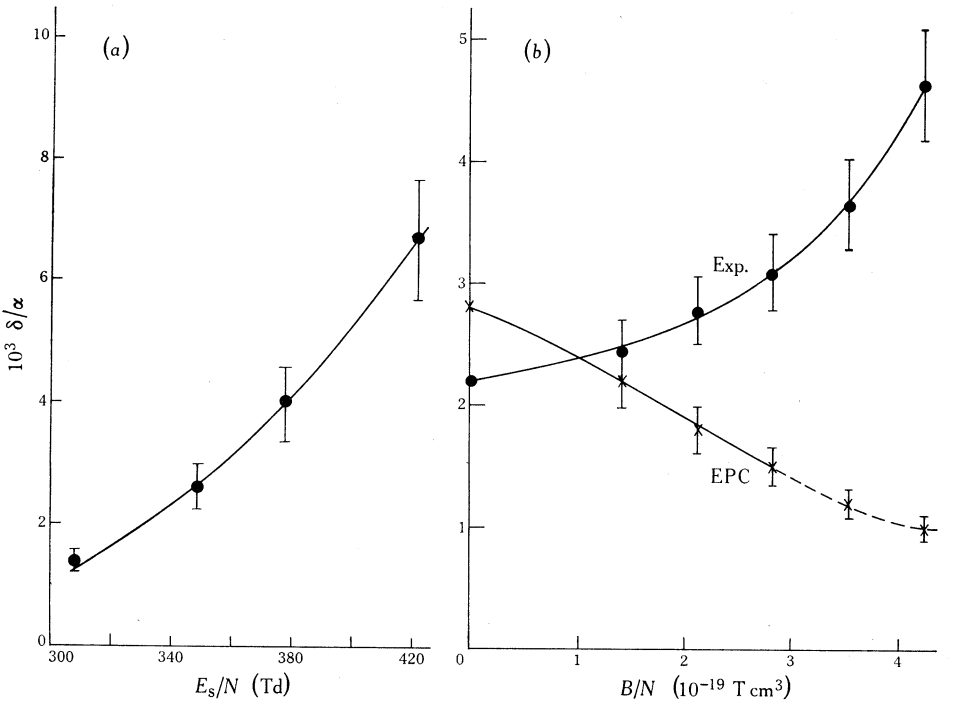

Fig. 4.—Determinations of the coefficient δ/α for photon impact at the cathode (*a*) as a function of E_s/N at $B/N = 0$, the errors bars indicating an uncertainty of $\pm 15\%$ in the experimental values of δ/α, and (*b*) as a function of B/N at $E/N = 350$ Td. The experimental results in (*b*) are compared with values calculated from the data in (*a*) using the equivalent pressure concept (EPC). The disagreement between the two curves in (*b*) at $B/N = 0$ is indicative of the change in δ/α from day to day due to long-term changes in the condition of the cathode surface.

IV. Conclusions

The present work has shown that the electrical breakdown of hydrogen in $E \times B$ fields can be explained in terms of one primary mechanism, ionization of gas molecules by electron impact, and only two secondary mechanisms, electron emission from the cathode initiated by positive ion impact and photon impact on it. There is no evidence

of the need to include any further mechanism, such as ionization of gas molecules by positive ion collision, in the range of E and B investigated here. Departures from the equivalent pressure concept observed in the present work on the δ/α process cast doubt upon any interpretation of the concept which demands that the form of the electron energy distribution is independent of the magnitude of the magnetic field. It should be noted that the validity of the theory of the equivalent pressure concept can only be rigorously established when it can be assumed that electron–molecule collisions are solely elastic and that the collision frequency is constant. Even in hydrogen, the gas for which this condition is most nearly obeyed, an effective collision frequency must be invoked which is not constant with swarm energy. The δ/α process, depending as it does on the detailed shape of the high energy tail of the electron energy distribution curve, presents a much more sensitive test of the concept. However, as the crucial test of the equivalent pressure concept, it would seem desirable to obtain direct experimental measurements of $F(\varepsilon, E/N, B/N)$ for comparison with determinations of $F(\varepsilon, [E/N])$.

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