A NEW METHOD FOR MEASURING THE ATTACHMENT OF SLOW ELECTRONS IN GASES*

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Introduction

Recent determinations of attachment and ionization coefficients have been carried out using a number of different techniques including (i) a method due in the first instance to Lozier using an electron beam (Craggs, Thorburn, and Tozer 1957 ; Tozer, Thorburn, and Craggs 1958), (ii) a development of Townsend's original method of determining ionization coefficients by the measurement of ionization currents between parallel plane electrodes of variable separation (Geballe and Harrison 1952, 1953), and (iii) a modification of Doehring's method depending on measurements of time of flight (Chanin, Phelps, and Biondi 1959). In experiments of the second and third type it is not possible to estimate experimentally the mean energy of the electrons and, if the coefficients are to be

* Manuscript received July 10, 1959.

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expressed as functions of electron energy, it is necessary to use the results of independent experiments.

Swarm experiments are particularly suitable when electrons of low mean energy are to be studied, since the presence of gas at relatively high pressure enables small energies to be maintained in the presence of high electric field strengths. Moreover, it is possible to measure simultaneously the coefficient of attachment α_a and the ratio W/D of drift velocity W to diffusion coefficient D for electrons, from which their mean energy may be estimated. Bailey and his colleagues (Healey and Reed 1941) developed a technique whereby pairs of values of α_a and W/D were obtained by measuring currents received by a series of electrodes of which all but the last contained a slit through which a fraction of the beam of electrons and ions passed. The purpose of this note is to describe briefly a new method of measuring the parameters and to report the results of preliminary experiments. Whereas no account was taken of the effect of ionizing collisions in the earlier work, it is possible with the present method to calculate the effect of such collisions on the measured values of α_a and W/D and an extension of the method will enable all three parameters to be determined.

Theoretical and Experimental Investigation

In a recent paper one of us (Huxley 1959) has given an account of a theoretical investigation of the structure of a stream of electrons and ions drifting and diffusing in a gas when ionization by collision and molecular attachment are present. If the source of the stream is a small hole in the cathode and the stream is entirely intercepted by an anode consisting of a central disk and two annuli, it has been shown that the expression for R, the ratio of the current received by the inner annulus to the total current received by both annuli, is given by

$$R=1-\frac{\dfrac{h}{d_b}\exp(\lambda h-\mu d_b)+\dfrac{\lambda h\alpha_a}{\mu}\displaystyle\int_0^1\exp(\lambda hs)\left\{\exp\left[-\mu h\left(\frac{b^2}{h^2}+s^2\right)^{\frac{1}{2}}\right]-\exp\left[-\mu h\left\{\frac{b^2}{h^2}+(2-s)^2\right\}^{\frac{1}{2}}\right]\right\}\mathrm{d}s}{\dfrac{h}{d_a}\exp(\lambda h-\mu d_a)+\dfrac{\lambda h\alpha_a}{\mu}\displaystyle\int_0^1\exp(\lambda hs)\left\{\exp\left[-\mu h\left(\frac{a^2}{h^2}+s^2\right)^{\frac{1}{2}}\right]-\exp\left[-\mu h\left\{\frac{a^2}{h^2}+(2-s)^2\right\}^{\frac{1}{2}}\right]\right\}\mathrm{d}s}, \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where h=length of the diffusion space,

$d_b=\sqrt{(b^2+h^2)}$,

$d_a=\sqrt{(a^2+h^2)}$, where a and b are the inner and outer radii of the inner annulus,

$$2\lambda=W/D=\frac{\text{drift velocity of electrons}}{\text{diffusion coefficient of electrons}}=40\cdot 29Z/k_1,$$

k_1=Townsend's energy factor,

$\mu^2=\lambda^2+2\lambda\alpha$,

$\alpha=\alpha_a-\alpha_i$=(attachment coefficient)$-$(ionization coefficient).

For the purpose of analysing the results of the present experiments it was assumed that ionization was small so that α could be set equal to α_a with little error.

Accordingly, sets of curves were prepared showing R as a function of μ and α_a for given values of h, from which μ and α_a may be found by measuring R at two values of h.

The experimental procedure is essentially as follows. A stream of electrons, having already acquired a steady state of motion in a uniform electric field Z, enters the diffusion chamber through a small hole in the cathode and moves through the gas under the same uniform field Z to the anode. The anode consists of separately insulated sections, the mode of division being described above. The purpose of the disk, which remains earthed throughout the course of the experiment, is to collect a central stream of unwanted ions which may have entered the diffusion chamber with the electrons. The experimental parameters are chosen so that all the ions entering at the source are collected by the central disk and so that an inappreciable current of electrons and ions falls outside the larger annulus.

In the present apparatus it is possible to vary the chamber length h continuously from 1 to 10 cm by means of an induction motor drive. Since the motor (excluding the field coils) and drive are totally enclosed within the evacuated envelope containing the diffusion apparatus it is possible to adjust the length without contaminating the sample of gas being investigated.

The procedure for determining α_a and k_1 simultaneously is as follows. At a given value of gas pressure p and electric field Z measurements of the ratio R are made at $h=2$ and 5 cm. The values of α_a and μ which satisfy equation (**1**) are found by a series of successive approximations using the graphs of R as a function of μ and α_a for the two values of h. As the first approximation α_a is set equal to 0 and, using the appropriate theoretical curves, the value of μ corresponding to the ratio R_2 for $h=2$ cm is determined. Using this value of μ, a closer approximation to α_a is obtained using the ratio R_5 obtained at $h=5$ cm and the theoretical curves for this value of h. The new value of α_a is used together with R_2 to determine a closer approximation to μ and so on. It was found that the values of α_a and μ converged quite rapidly to limiting values, usually after three " cycles ".

Having determined μ and α_a, k_1 is determined as follows. Since $\mu^2=\lambda^2+2\lambda\alpha_a$, when $\alpha_i=0$, then $\mu-\lambda=2\lambda\alpha_a/(\mu+\lambda)\simeq\alpha_a$, since $\alpha_a\ll\mu$, so that $\lambda=\mu-\alpha_a$ to a sufficient degree of accuracy. Then, since $2\lambda=W/D=40\cdot29\,Z/k_1$ at 15 °C,

$$k_1=20\cdot15\,Z/\lambda.$$

As a check on the reliability and self-consistency of the method a set of values of α_a for $Z/p=5$ V cm^{-1} (mm Hg)$^{-1}$ has been derived from measurements made with four different combinations of pressure p and diffusion chamber length h. In addition, an exact analysis of the composition of the mixed stream of electrons and ions, taking into account the diffusion of the ions formed by attachment, was undertaken by Dr. C. A. Hurst of the Department of Mathematical Physics. He showed that the ion current terms in the expression for R must be modified by correction factors which are functions of h, k_1, and α, but calculation showed their effect to be negligible in analysing the results of the present experiments.

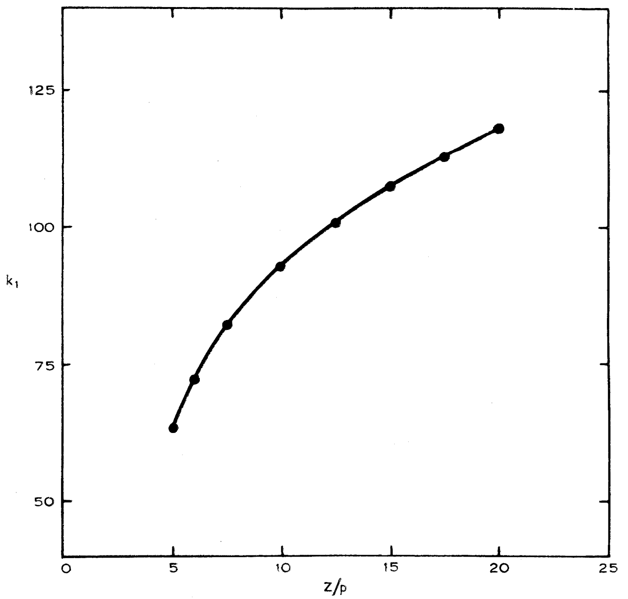

Fig. 1.—Townsend's energy factor k_1 plotted as a function of Z/p.

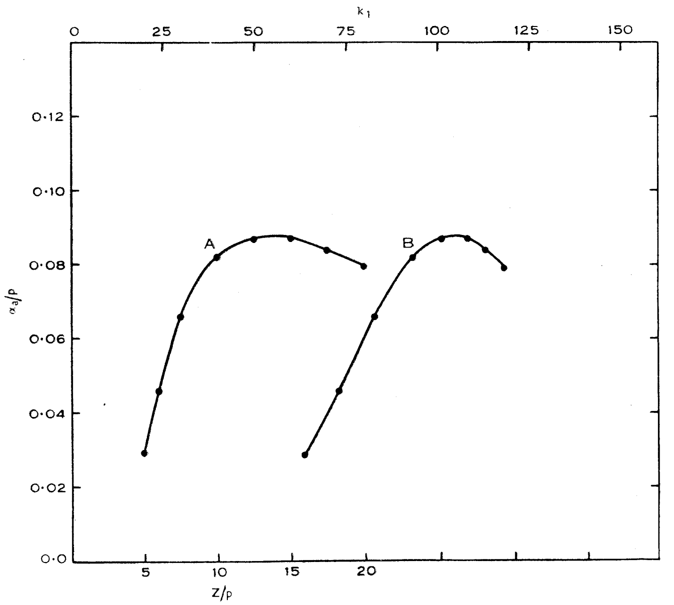

Fig. 2.—Curve A, α_a/p plotted as a function of Z/p. Curve B, α_a/p plotted as a function of Townsend's energy factor k_1.

Results

The two tables and two diagrams given summarize the first measurements made with the new method. In a sample of oxygen at 2 mm Hg pressure values of α_a/p have been obtained in the range $5 \leqslant Z/p \leqslant 20$ V cm^{-1} (mm Hg)$^{-1}$ from coupled measurements of R made at $h=2$ and 5 cm. The electron energy factor k_1 has also been derived from the measurements in this range by the process

TABLE 1

SUMMARY OF THE RESULTS IN OXYGEN FOR $5<Z/p<20$ V CM^{-1} (MM Hg)$^{-1}$

Z/p	α_a	μ	λ	α_a/p	k_1
5	0·058	3·24	3·18	0·029	63·3
6	0·092	3·41	3·32	0·046	72·8
7·5	0·133	3·79	3·66	0·066	82·6
10	0·164	4·48	4·32	0·082	93·3
12·5	0·174	5·16	4·99	0·087	101
15	0·173	5·79	5·62	0·087	108
17·5	0·168	6·41	6·24	0·084	113
20	0·158	6·97	6·81	0·079	118

explained earlier. Table 1 summarizes the results obtained at a pressure of 2 mm Hg, while Table 2 shows the self-consistency of the method for various combinations of pressure and chamber length. Figures 1 and 2 present the results in graphical form.

The results obtained for $Z/p=20$ V cm^{-1} (mm Hg)$^{-1}$ were further analysed to determine the effect of ionization by collision upon the calculated values of α_a. Geballe and Harrison (1953) have published values of α_i/p as a function of Z/p

TABLE 2

SHOWING THE SELF-CONSISTENCY OF THE RESULTS AT $Z/p=5$ V CM^{-1} (MM Hg)$^{-1}$ FOR DIFFERENT VALUES OF p AND h

Oxygen Pressure (mm)	From Measurements at $h=2$ and 5 cm	From Measurements at $h=2$ and 10 cm
5	0·032	0·031
10	0·032	0·033

for values of $Z/p>25$ V cm^{-1} (mm Hg)$^{-1}$, from which, by use of Townsend's formula $\alpha_i/p=A \exp[-B/(Z/p)]$ (Loeb 1955), a value of $\alpha_i/p=0{\cdot}012$ for $Z/p=20$ V cm^{-1} (mm Hg)$^{-1}$ was estimated. This value of α_i/p was used to recalculate a section of the theoretical curves appropriate to the analysis of the results obtained at $p=2$ mm Hg for $Z/p=20$ V cm^{-1} (mm Hg)$^{-1}$. A value of $\alpha_a=0{\cdot}162$ resulted from the reassessment compared with the value 0·158 obtained previously when ionization was ignored; k_1 was modified correspondingly from $k_1=118$ to $k_1=117$. In the range of values of $Z/p<20$ V cm^{-1} (mm Hg)$^{-1}$ over which α_i/p is appreciable, α_i/p decreases and α_a/p increases as Z/p decreases, so that the discrepancy of $2\frac{1}{2}$ per cent. in α_a/p at $Z/p=20$ V cm^{-1} (mm Hg)$^{-1}$ represents the maximum discrepancy to which the values in Table 1 are subject due to the assumption that $\alpha_i=0$.

Throughout the experiments the ratios R were measured to an accuracy of the order of 1 per cent. An examination of the theoretical curves shows that an error of this magnitude will in general lead to an error in α_a of approximately 5 per cent., although a somewhat larger error may be expected for small values of μ, that is, where measurements at small values of Z/p are carried out at low pressure. The discrepancy between the value of α_a/p at $Z/p=5$ V cm^{-1} (mm Hg)$^{-1}$ obtained at a pressure of 2 mm Hg and the more consistent values obtained at 5 and 10 mm Hg may be accounted for on this basis. Values of k_1 are less affected by experimental error in the ratio R, and the results for this parameter obtained at pressures of 2, 5, and 10 mm Hg agree to within 2 per cent.

The authors wish to express their indebtedness to Dr. B. I. H. Hall, formerly of this Department, for carrying out the initial calculation of some of the theoretical curves and to Mr. J. Gascoigne for the construction of the diffusion apparatus.

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