

THE MEASUREMENT OF ELECTRON DRIFT VELOCITIES*

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Several methods (Loeb 1955; Breare and von Engel 1964; Raether 1964) have been devised to measure the drift velocity W of electrons moving under the influence of an electric field E through a gas at pressure p . The most accurate method is that of Bradbury and Nielsen (1936) (see also Lowke 1963), but for reasons discussed below this technique has been limited to low values of E/p . We have found that the useful range of this method can be greatly extended by some modification to the conventional form of the apparatus.

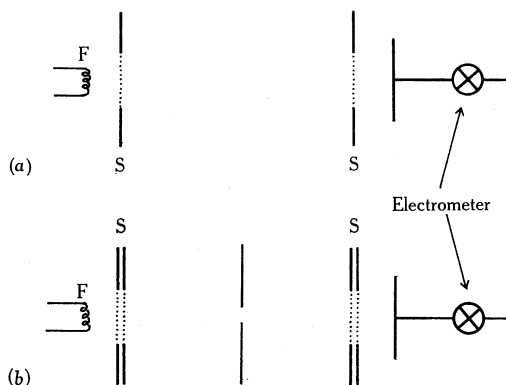


Fig. 1.—Schematic diagrams of (a) the Bradbury-Nielsen apparatus for the measurement of electron drift velocities, and (b) the present apparatus showing modifications to the Bradbury-Nielsen method.

An apparatus of the Bradbury-Nielsen type is indicated in Figure 1(a). Electrons emitted from the filament F move in a uniform electric field (maintained by guard rings) to a collecting plate where the electron current is measured. The shutters S each consist of a plane grid of parallel wires with alternate wires connected together. An a.c. voltage is applied between adjacent wires so that the electron stream is divided into a series of pulses by the first shutter, the transmission of the shutter being greatest when the alternating voltage passes through zero. The second shutter acts in a similar manner so that the transmitted current is a maximum when the transit time of electrons moving between the shutters is equal to integral multiples

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of the half-period of the a.c. voltage. A current-frequency graph shows a number of maxima and the drift velocity is given by

$$W = 2f_n d/n, \quad (1)$$

where f_n is the frequency corresponding to the n th maximum and d is the distance between the shutters.

As E/p increases, the current maxima become more difficult to distinguish and this limits the E/p range for which the method can be used. The decrease in sensitivity arises through two effects:

- (1) At higher electron energies the gating action of the shutters becomes less effective and the electron stream is no longer divided into separate pulses but becomes continuous, with the spatial variation in electron density decreasing with increasing E/p .
- (2) The pd values that can be used for a given E/p are limited both by gas breakdown and by significant contributions to the measured current from electrons produced by positive ions and photons in the drift region. For increasing E/p the largest pd values obtainable must decrease, so that the diffusion broadening of each pulse becomes more pronounced.

In order to improve the gating action of the shutters, the Bradbury-Nielsen type were replaced by a double grid system as shown in Figure 1(b), with the a.c. voltage applied between adjacent grids. This type of shutter has been used for the measurement of positive ion mobilities (Loeb 1955). With this arrangement, maximum transmission through each shutter occurs when the a.c. voltage is a maximum and in the same sense as the applied d.c. field. When the a.c. voltages applied to each shutter are in phase, the drift velocity is given by

$$W = f_n d/n. \quad (2)$$

If the a.c. voltages applied to each shutter are 180° out of phase then

$$W = 2f_n d/(2n-1). \quad (3)$$

Although this method introduces some uncertainty in the determination of the drift distance d , the errors can be kept small. In the present apparatus the grid separation is 1% of the drift distance (15 cm). Effects of a.c. field penetration in the drift region are minimized by ensuring that the alternating voltage is small compared with the d.c. voltage between the shutters. We have used alternating voltages up to 3.5 V r.m.s. while the d.c. voltage was in the range 500–800 V and have not observed any variation in the position of the maxima. Another disadvantage of this system is that electrons entering the drift space are not in equilibrium with the field. However, if the pd value is sufficiently large, the time taken for equilibrium to be obtained can be made small compared with the drift time. All these factors can be investigated experimentally by changing the relevant parameters.

Using this type of shutter, current maxima have been observed in hydrogen for E/p in the range $0 < E/p < 100 \text{ V cm}^{-1} \text{ torr}^{-1}$, the upper limit being determined in

the present apparatus by the capacitive loading of the shutter system on the a.c. supply at high frequencies. Previous measurements of W in hydrogen by the Bradbury-Nielsen method were limited to E/p values in the range $0 < E/p < 20$. In this first version of our apparatus the peaks could be located to an accuracy of $\pm 4\%$ (the inaccuracy being mainly caused by unstable filament emission) and the E/p value could be set to within $\pm 3\%$ (the error being principally due to inaccuracies in pressure measurement). A current-frequency graph for $E/p = 69 \text{ V cm}^{-1} \text{ torr}^{-1}$ (at 20°C) is shown in Figure 2. When calculating the value of W from such current

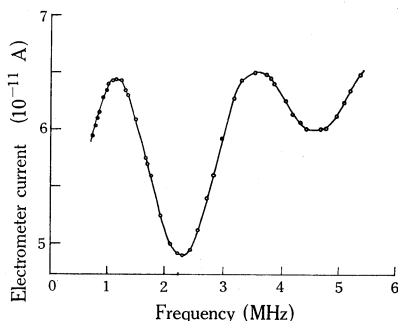


Fig. 2.—Electrometer current as a function of the frequency of the shutter voltage for $E/p = 69 \text{ V cm}^{-1} \text{ torr}^{-1}$ ($p = 0.55 \text{ torr}$) at 20°C in hydrogen.

maxima it is necessary to apply correction terms to equations (1), (2), and (3) to allow for diffusion of the electron bunches and for ionizing collisions at higher values of E/p . When E/p is sufficiently small so that ionization in the gas does not contribute significantly to the total measured current, Lowke (1962) has shown that the value W' of the drift velocity calculated using equation (1) is related to the true drift velocity W by the equation

$$W' = W[1 + C\{d(W/D)\}^{-1}], \quad (4)$$

where D is the diffusion coefficient for electrons and C is a constant whose value is determined by the particular experimental conditions. For a given E/p the value of W can be found by plotting W' against $(pd)^{-1}$ and extrapolating the graph to $(pd)^{-1} = 0$. A similar procedure can be adopted for the modified form of the apparatus, where W' is calculated from either equations (2) or (3).

At higher values of E/p the determination of W from W' is more difficult. Lucas (1964) has derived an expression for the spatial electron distribution in an avalanche when ionization occurs and this result (equation (2) of Lucas 1964) can be used in an analysis of the current-frequency curves similar to that carried out by Lowke (1962). Assuming that $dW/D \gg 1$ the expression for W' then becomes

$$W' = W[1 + C\{d(W/D)\}^{-1} - 2\alpha(W/D)^{-1}], \quad (5)$$

where α is the first Townsend ionization coefficient. Again the term $C\{d(W/D)\}^{-1}$ can be found experimentally by plotting W' against $(pd)^{-1}$. However, the term $2\alpha(W/D)^{-1}$ is not dependent upon pd for a given E/p and must be measured independently. The major difficulty in this procedure is in assessing the validity of the

expression given by Lucas. An alternative expression has been given by Brambring (1964), Schlumbohm (1965), and Ward (1965)* and leads to the result

$$W' = W[1 + C\{d(W/D)\}^{-1} - \alpha(W/D)^{-1}]. \quad (6)$$

The difference in the expressions given by Lucas and by Brambring arises through the assumptions made regarding the ionization frequency ν_i for electrons in a diffusing avalanche. Lucas assumes that ν_i is constant throughout the avalanche and defines $\alpha = \nu_i/W$, the average number of ionizing collisions made by an electron in moving unit distance in the direction of the electric field. The derivations given by Brambring, Schlumbohm, and Ward have *implicitly* assumed a variation of ν_i throughout the avalanche and have defined α in a different manner. Since any variation of ν_i implies a variation in the electron energy distribution throughout the avalanche, it is not consistent to assume D to be constant, as the latter authors have done. While it appears reasonable on physical arguments that ν_i should not remain constant throughout the avalanche, the formulation given by these authors cannot be justified until a complete treatment by way of the Boltzmann equation is available. It seems to the present authors that further work along these lines is required before an assessment can be made of the validity of equations (5) and (6).

In order to improve further the sharpness of the measured current peaks, it would be advantageous to work with pd values as large as the approach to breakdown will allow. It has been found that by inserting a thin metal plate with a small central hole at the midpoint of the drift space (see Fig. 1(b)) the values of pd can be greatly increased before breakdown occurs. This would allow sharper current maxima to be obtained, but in the present experiments the drift in filament emission was still the limiting factor in determining the current peaks. Improved stability is required in order to assess the merits of this procedure. Lateral diffusion to the central plate will modify the electron distribution in the avalanche and will increase the diffusion effects discussed above. As in the previous case these can be determined experimentally by taking measurements of W' for several values of pd at a constant value of E/p . The application of a longitudinal magnetic field would also reduce the lateral diffusion without modifying the value of the drift velocity. Using the apparatus described here the diameter of the hole in the central plate has been varied from 0.2 to 2.0 cm, but the variation observed in W' was only of the same order (4% at 0.5 torr pressure) as the experimental accuracy and decreased with increasing pressure.

The influence of secondary electrons produced by photons and ions at electrode surfaces has not been included in the above analysis, and pd values must not be so large that these secondary electrons and their associated avalanches form a significant part of the total current. The importance of these secondary electrons can be minimized by the insertion of the central plate since photons produced in the second half of the drift space and directed towards the first shutter will be largely absorbed by the plate. Any secondary electrons produced there will have a smaller distance of travel in which to produce additional ionization.

* This paper was brought to our attention by Dr. R. W. Crompton (Australian National University, Canberra), and we are indebted to him for illuminating discussion on this aspect of our work.

A detailed investigation of the corrections to be applied to W' requires a greater experimental accuracy than that obtained in the present initial experiments. A second drift tube ($d = 25.6$ cm) has been constructed and the values of W' can now be determined to an accuracy of about 1%.

In correcting the measured values of W' for diffusion, additional errors arise through the extrapolation procedure. Using this second drift tube the overall accuracy for the extrapolated values of W varies from about 2% at $E/p = 12.0$ to 3% at $E/p = 50$. Table 1 shows the results obtained for W in hydrogen with $E/p \leq 50$. For this range of E/p values the ionization correction term and the effects of secondary

TABLE 1
ELECTRON DRIFT VELOCITY IN HYDROGEN

E/p at 20°C (V cm ⁻¹ torr ⁻¹)	$W \times 10^{-7}$ (cm/sec)	E/p at 20°C (V cm ⁻¹ torr ⁻¹)	$W \times 10^{-7}$ (cm/sec)
12	0.423	30	1.15
15	0.510	35	1.38
18	0.617	40	1.68
20	0.702	45	1.89
25	0.915	50	2.16

electron production at the electrodes are not important. The present results are in good agreement with those given by Lowke (1963) for $E/p \leq 18$.

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