

THE DRIFT VELOCITY OF ELECTRONS IN CARBON DIOXIDE AT 293°K

By M. T. ELFORD*

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Summary

The drift velocity of electrons in carbon dioxide at 293°K has been measured with an error of less than 0.5% over the range $0.3 \times 10^{-17} \text{ V cm}^2 < E/N < 9.1 \times 10^{-17} \text{ V cm}^2$ and 1% over the range $9.1 \times 10^{-17} \text{ V cm}^2 < E/N < 21.2 \times 10^{-17} \text{ V cm}^2$. The accuracy of the available data is discussed.

INTRODUCTION

In recent years, considerable advances have been made in the theoretical derivation of the elastic and inelastic cross sections from the electron transport coefficients for electrons moving in a gas under the influence of a uniform electric field (Crompton and Huxley 1962; Frost and Phelps 1962; Pack, Voshall, and Phelps 1962; Crompton and Jory 1965). Since the accuracy of the cross sections so obtained is dependent on the accuracy of the experimental measurements of the transport coefficients, it is important that the experimental error be minimized. In the case of carbon dioxide, the data available for one of the transport coefficients, the drift velocity W (cm/sec), show considerable disagreement. For instance, two of the more recent sets of data, i.e. those of Bortner, Hurst, and Stone (1957) and Pack, Voshall, and Phelps (1962), disagree by up to 10%.

Measurements have been made with higher accuracy than previously available in drift velocity measurements in order to resolve the differences between the data obtained by various workers and methods and also to make available data with an error of less than 0.5% for use in the analyses already described.

APPARATUS

The method used to measure the electron drift velocity, that of Bradbury and Nielsen (Nielsen 1936), has been fully described by Lowke (1963*a*), while details of the experimental tube will be given by Crompton and Jory (paper in preparation). Before taking the present measurements, several modifications were made to improve the control and measurement of the gas temperature. The tube was immersed in a water bath and the gas temperature determined by a copper-constantan thermocouple to within 0.1 degC. The temperature of the water bath was stable to within 0.1 degC per hour. The gas pressures were measured by a

* Ion Diffusion Unit, Australian National University, Canberra.

Texas quartz spiral gauge which was checked against a CEC type 6201 primary pressure standard. The error in pressure measurement is less than 0.1% for all the gas pressures used (see Table 1).

In the Bradbury-Nielsen method, if the electron current arriving at the collector electrode is plotted as a function of the frequency of the alternating potential applied to the grids, the curve consists of a series of maxima and minima, the maxima occurring at frequencies f_0, f_1, \dots, f_n , where $f_n = nf_0$ and n is an integer. Since the determination of the frequencies f_0, f_1, \dots enables the transit time and hence the drift velocity of the electrons to be determined, considerable care is required in the measurement of these frequencies. Three conditions are necessary if these measurements are to be made with adequate precision.

First, the resolving power must be sufficiently high. The resolving power is defined as the ratio of the frequency at which the maximum current occurs divided by the frequency spread at half-maximum current. The maximum resolving power, which is determined by the diffusion of the electron groups, is given approximately by

$$(\text{resolving power})_{\text{max}} = \frac{1}{4} \left(h \frac{W}{D} \frac{1}{\ln 2} \right)^{\frac{1}{2}} \quad (\text{Lowke 1963b}),$$

where h = distance between the planes of the Bradbury-Nielsen grids
 (= 9.991 ± 0.003 cm),

D = diffusion coefficient.

The maximum resolving power is greater than 8 for all values of E/p and p used in the present measurements (E is the electric field strength in V/cm and p is the gas pressure in torr). Since a resolving power of 5 is sufficient for measurements to be made with adequate precision, the maximum resolving power did not limit the accuracy of the present results.

In practice, the resolving power is a function not only of the diffusion of the electron groups but also of the amplitude of the alternating potential applied to the grids. In the present measurements, the alternating potential required to produce a resolving power of 5 or greater at low values of E/p is only of the order of 0.5 V (peak-to-peak), while at the highest values of E/p the voltage was greater than 10 V (peak-to-peak). These measurements at high E/p required frequencies of the order of 0.5 Mc/s, and the voltage that could then be supplied to the grids was limited by the onset of distortion of the sinusoidal waveform resulting from the low impedance of the shutters, whose capacity is approximately 2000 pF. This difficulty precluded the taking of measurements at values of E/p greater than 7.

Secondly, the method of determining the frequencies f_0 and f_1 must be sufficiently accurate. To achieve the best accuracy, the frequency should be measured under conditions where the change in electron current is large for small changes in the frequency. The method used was therefore the following. A value of the electron current approximately 50% of the maximum value, which was of the order of 10^{-11} A, was chosen and the frequency at which this value occurred on both sides of the maximum measured by a frequency counter. The mean of these two frequencies gives an accurate estimate of the frequency at which the maximum value of the

electron current occurs. Two progressively larger values of electron current were chosen and the procedure repeated, the best estimate of the frequency being obtained by averaging the three values. If the maximum is asymmetrical, the three estimates of the frequency f_n will show a progressive trend as the current chosen increases. In no set of measurements was this effect observed. Both f_0 and f_1 were measured, and since f_1 should be exactly twice f_0 an excellent experimental check is provided. In every measurement made, $f_1/2$ agreed with f_0 to within 0.1%, the mean of these two values being taken as the best estimate of the frequency of the first maximum.

Thirdly, the electron current must be held sufficiently stable over the period of measurement. Since, however, the time taken to measure the two frequencies on either side of a maximum is only 15 sec approximately, this requirement is not difficult to satisfy. The electron current was obtained from a heated platinum filament, the heating current being highly stabilized.

At the highest gas pressure used (50 torr) and the lowest values of E/p , two effects were observed. The emission from the platinum filament was found to be unstable, decaying rapidly with time, and a large negative ion background was observed in the electron current versus frequency curves. The negative ions were presumably O_2^- formed by attachment of the thermal-energy electrons to impurity oxygen molecules. The presence of the oxygen molecules resulted from the outgassing of the platinum filament. To reduce this outgassing, the platinum filaments were heated to dull red in an atmosphere of hydrogen for 1 hour. After this treatment the filaments gave stable electron currents, and no negative ion current could be detected in subsequent measurements.

The experimental tube was pumped to a pressure of less than 1×10^{-6} torr by a 5 litre/sec Vacion pump before gas was admitted. The rate of rise of pressure of the experimental tube was less than 5×10^{-5} torr per hour in the absence of liquid nitrogen traps. This pressure rise corresponds to a rate of rise of impurity level of less than 10 p.p.m. per hour into a gas sample at a pressure of 5 torr. It was shown that the outgassing of the tube has a negligible effect on the results by making measurements with the same gas sample over a 12 hr period. The change in the measured drift velocity was less than 0.2%. The carbon dioxide used was Airco research grade.

RESULTS

The experimental values are shown in Table 1 and in Figure 1. The experimental scatter of the present results is $\pm 0.2\%$. Since the width of the line representing these results is approximately 5%, all the experimental results lie within the width of this line and have therefore not been shown. The gas temperature and pressure were measured after each measurement of the drift velocity and, for the purpose of producing Table 1, a small correction made (less than 0.5%) to normalize the measured drift velocity to that corresponding to an integral value of E/p_{293} . (The subscript 293 refers to the temperature in degrees Kelvin to which the pressure is normalized.) Table 1 also lists the results as a function of E/N , where $E/N = 3.03 \times 10^{-17} E/p_{293}$ V cm² and N is the gas number density.

By tabulating the results at each value of E/p_{293} as a function of gas pressure, it is possible to determine whether diffusion errors are present (Lowke 1962). These errors cause the values of the measured drift velocity to increase as the pressure decreases at a given value of E/p . The magnitude of the error is estimated from the expression

$$W' = W \left(1 + \frac{3}{h W/D} \right),$$

where W' = measured drift velocity,
 W = true drift velocity.

TABLE I
 DRIFT VELOCITY OF ELECTRONS IN CARBON DIOXIDE AT 293°K
 Values of p are in torr

E/p_{293} (V cm ⁻¹ torr ⁻¹)	$E/N \times 10^{17}$ (V cm ²)	$W \times 10^{-5}$ (cm/sec)				Average $W \times 10^{-5}$ (cm/sec)
		$p = 5$	10	20	50	
7.0	21.24	68.4				68.4
6.0	18.20	54.7				54.6
5.0	15.17	39.9				39.9
4.0	12.14	27.31				27.31
3.0	9.10	18.18	18.19			18.19
2.5	7.59	14.55	14.57			14.56
2.0	6.07	11.25	11.27			11.26
1.8	5.46	10.02	10.04	10.02		10.03
1.5	4.55	8.248	8.242	8.245		8.24 ₅
1.2	3.64	6.533	6.539	6.536		6.53 ₆
1.0	3.03	5.421	5.425	5.421		5.42 ₂
0.9	2.73	4.869	4.865	4.871		4.86 ₈
0.8	2.43	4.322	4.327	4.322		4.32 ₄
0.7	2.124	3.780	3.785	3.783	3.786	3.78 ₄
0.6	1.820	3.236	3.240	3.245	3.244	3.24 ₁
0.5	1.517	2.698	2.700	2.699	2.704	2.70 ₀
0.4	1.214	2.158	2.158	2.162	2.162	2.16 ₀
0.3	0.910		1.621	1.620	1.621	1.621
0.25	0.759		1.350	1.351	1.352	1.351
0.2	0.607			1.080	1.081	1.081
0.18	0.546			0.972	0.972	0.972
0.15	0.455			0.811	0.811	0.811
0.12	0.364			0.649	0.651	0.650
0.1	0.303				0.541	0.541

The error has been calculated for all values of E/p_{293} and E used in the present measurements, using the values of W/pD measured by Rees (1964). With the exception of the values at $E/p = 6$ and 7, the maximum difference between W and W' is less than 0.2%. The error predicted at $E/p = 7$ is 0.6%, but previous measurements made in helium suggest that the expression above overestimates the error for a grid spacing of 10 cm; in fact, the results in Table I show that for all values of E/p the diffusion errors are difficult to detect above the small experimental scatter of the measurements. The final values for the electron drift velocity

were therefore obtained by averaging the values taken at the various pressures and are considered to be in error by less than 0.5% for $0.1 < E/p_{293} < 3.0$ and 1% for $4.0 < E/p_{293} < 7.0$.

DISCUSSION

Four previous sets of electron drift velocity measurements have been made in carbon dioxide (Skinker 1922; Rudd 1932 (cited by Healey and Read 1941); Bortner, Hurst, and Stone 1957; Pack, Voshall, and Phelps 1962). The first two, those of Skinker and Rudd, employed the Townsend magnetic deflection method.

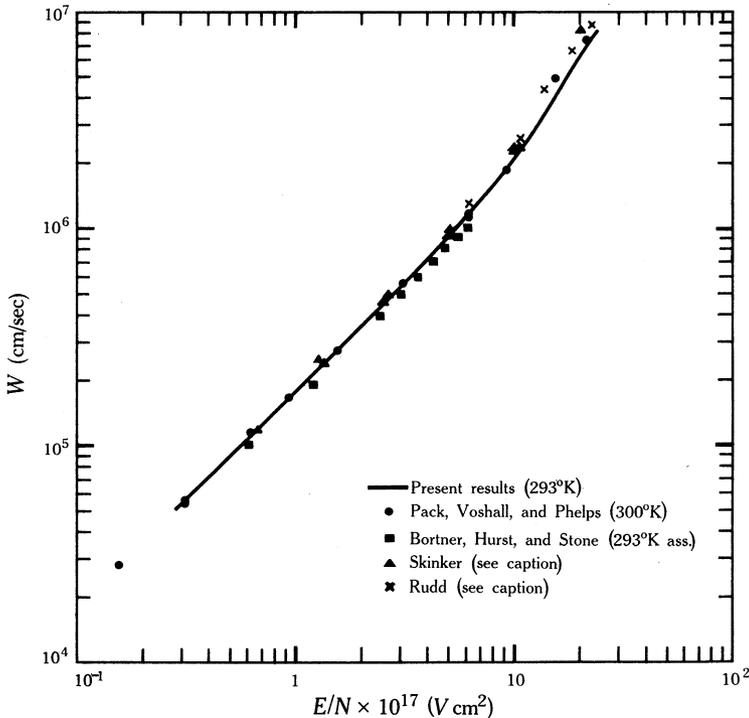


Fig. 1.—Drift velocity of electrons in carbon dioxide at 293°K as a function of E/N . (Note: The measurements of Skinker and Rudd have been included only to facilitate the discussion; the method used by these workers does not result in a measurement of the true electron drift velocity except under special circumstances.)

This method has been shown by Townsend (1937) and Huxley (1937) to be an indirect method of measurement, since it involves a knowledge of the velocity distribution function and the energy dependence of the momentum transfer cross section. Large errors can occur by neglecting these factors (Jory 1965). The method is accurate only if the momentum transfer collision frequency ν_m is constant. Pack, Voshall, and Phelps (1962) have shown that ν_m is constant for electrons in carbon dioxide over the energy range 0.01–0.07 eV, and hence it would be expected that measurements made by magnetic deflection methods would agree with the present results in this energy range. The values of Skinker are in fact in fair agreement

with both the present results and those of Pack, Voshall, and Phelps for values of E/N less than about 6×10^{-17} V cm², at which value the mean electron energy is approximately 0.07 eV. Since the energy dependence of ν_m is unknown at higher energies, no direct comparison of either Skinker's or Rudd's results should be made with the present results. It should be noted that neither Skinker nor Rudd state the temperature at which the gas pressure was measured. In order to convert their values, which were published as a function of E/p , to values as a function of E/N , a gas temperature of 293°K has been assumed.

Figure 1 also shows the values of Bortner, Hurst, and Stone (1957), who measured the drift velocity by a time-of-flight technique employing Geiger counters. A temperature of 293°K has again been assumed to convert their values of E/p to E/N . Their values are systematically 10% below both the present values and those of Pack, Voshall, and Phelps. Recent measurements by Wagner and Davis (personal communication 1966) using a similar method are considerably closer to the present values than the earlier measurements of Bortner, Hurst, and Stone, and it would therefore appear that the earlier values are in error by approximately 10%.

The measurements of Pack, Voshall, and Phelps were made by a time-of-flight technique employing pulsed ultraviolet radiation to produce photoelectrons and two Bradbury-Nielsen grids which could be operated by pulses at controlled time intervals. The agreement between their results and the present values is within 2% up to $E/N = 1 \times 10^{-16}$ V cm², but their two measurements at values of E/N greater than this differ by up to 20%.

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