ELECTRON DRIFT AND DIFFUSION IN DEUTERIUM AT 293°K

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[*Manuscript received July* 20, 1966]

Summary

The drift velocity and the ratio of diffusion coefficient to mobility have been measured for electrons in deuterium at 293°K over the ranges $0 \cdot 006 \leqslant E/p \leqslant 5 \cdot 0$ and $0 \cdot 006 \leqslant E/p \leqslant 2 \cdot 0$ respectively. The results are compared with those of other workers.

I. Introduction

When a swarm of electrons drifts and diffuses through a gas under the influence of an electric field, the energy gained from the field by the electrons is transferred to the gas by the various elastic and inelastic collision processes that occur. Cross sections for these processes can be determined from accurate values of the electron drift velocity W and the ratio of diffusion coefficient to mobility D/μ (see, for example, Frost and Phelps 1962 or Crompton and Jory 1965).

The present paper reports values of W and D/μ for electrons in deuterium at 293°K over the ranges $0 \cdot 006 \leqslant E/p \leqslant 5 \cdot 0$ and $0 \cdot 006 \leqslant E/p \leqslant 2 \cdot 0$ respectively, where E is the electric field strength in V/cm and p is the gas pressure in torr. An error limit of $\pm 1\%$ is placed on the values of D/μ, while for the values of W the error limit is $\pm 1\%$ for $0 \cdot 006 \leqslant E/p \leqslant 1 \cdot 2$ but $\pm 2\%$ for $1 \cdot 2 < E/p \leqslant 5 \cdot 0$.

II. Experimental Procedure and Apparatus

The drift velocities were determined by an a.c. electrical shutter method developed by Bradbury and Nielsen (1936) and critically examined by Lowke (1962). The apparatus and experimental techniques are to be described in detail elsewhere (Crompton and Jory, in preparation; Elford 1966).

The ratio of diffusion coefficient to mobility was measured by the Townsend–Huxley lateral diffusion method using apparatus and techniques identical with those described by Crompton, Elford, and Gascoigne (1965). Small errors caused by contact potential differences over the surfaces presented to the electron stream were eliminated, or compensated for, by the application of a small potential difference between the guard rings and the end plates of the apparatus (Crompton, Elford, and Gascoigne 1965). Two sets of measurements were taken in the same apparatus but with different collecting electrodes requiring different compensating potentials. At the lowest value of electric field strength used ($3 \cdot 0$ V/cm) and with *no* compensating potential applied, an error in D/μ of approximately $1 \cdot 5\%$ occurred with one of the collecting electrodes while the corresponding error for the other electrode used was $0 \cdot 7\%$. Results obtained after the application of compensating potentials were in excellent agreement with each other at all field strengths.

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The experimental tubes were evacuated to less than 10^{-6} torr with 5 litre/sec "Vacion" pumps. The rate of rise of pressure in the drift velocity apparatus when isolated from the pumps but connected to liquid nitrogen traps was 8×10^{-6} torr/hr, corresponding to a gas influx of approximately 1×10^{-8} torr litre/sec. For the lateral diffusion apparatus the corresponding values were 4×10^{-6} torr/hr and 5×10^{-9} torr litre/sec. Over the time taken for any experimental run these gas influxes would lead to a maximum impurity concentration of 5 p.p.m. at the lowest pressures used and concentrations of proportionately less than this over the remainder of the pressure range. Calculations show that impurities of this concentration have a negligible effect on the values of W and D/μ.

The deuterium gas, which was stated by the manufacturer (General Dynamics Corporation) to contain not less than $99\cdot9\%$ of the isotope, was admitted to the apparatus through a heated palladium osmosis tube and two liquid nitrogen traps. The small amounts of hydrogen and deuterium hydride admitted in this way would affect both W and D/μ by approximately $0\cdot1\%$. Impurities other than the hydrogen isotopes should be less than 1 p.p.m. (Young 1963).

III. Results and Discussion

(a) *Drift Velocity*

In the Bradbury and Nielsen shutter method a graph of the transmitted current as a function of the frequency applied to the shutters shows a series of maxima and minima, the amplitude of which decreases with increasing frequency. At constant E/p the maxima and minima should occur at integral multiples of a characteristic frequency f_0 such that $1/2f_0$ is the transit time of the electrons between the shutters. For each E and p the frequencies corresponding to the first two maxima were determined (Elford 1966). In every case the values of the drift velocity found in this way were in agreement with each other to within $0\cdot2\%$; the agreement was often considerably better than this.

Lowke (1962) has analysed the errors due to diffusion in drift velocity measurements and has shown that, to a good approximation, the observed drift velocity W' is related to the true drift velocity W by the relation

$$W' = W\{1+3(hW/D)^{-1}\}, \tag{1}$$

in which h is the distance between the planes of the shutters and D is the diffusion coefficient. The magnitude of this correction decreases with increasing p at a given value of E/p and in many gases, including deuterium, it decreases with increasing E/p at a given value of p. In the present apparatus h is 10 cm and so the errors due to diffusion are much less than they would be in a shorter apparatus.

The values of W' are listed in Table 1. The agreement of the values taken at the same E/p but different p is good, but is made even better by correcting the results for the effects of diffusion using equation (1). There was, however, some evidence that the term $3(hW/D)^{-1}$ overestimates the correction to be applied, particularly at the higher values of E/p. The "best estimate" values of W in Table 1 were obtained by the application of equation (1) to the result taken at the highest pressure for each value of E/p, since these results are less subject to diffusion errors and to errors from contact potential differences within the apparatus. Where results were taken over a sufficiently wide range of pressure, values of W identical to the best estimate values could be obtained by plotting W' against p^{-1} and extrapolating to $p^{-1} = 0$.

TABLE 1

DRIFT VELOCITY OF ELECTRONS IN DEUTERIUM AT 293°K

E/p	$W' \times 10^{-5}$ (cm/sec) at p (torr) of:									Best Estimate of $W \times 10^{-5}$ (cm/sec)
	500	400	300	200	100	50	20	10	5	
0·006	0·281(9)	0·282(1)								0·281(2)
0·007	0·328	0·328								0·327
0·008	0·373	0·373								0·372
0·009	0·418	0·418								0·417
0·010	0·463	0·463	0·464							0·462
0·012	0·551	0·552	0·552							0·550
0·015	0·679	0·679	0·680	0·683						0·678
0·018	0·802	0·803	0·804	0·807						0·802
0·020	0·882	0·884	0·884	0·887						0·882
0·025	1·076	1·076	1·077	1·079						1·075
0·03	1·258	1·258		1·260	1·266					1·257
0·04	1·593	1·594	1·596	1·601	1·604					1·592
0·05	1·896	1·897	1·898	1·904	1·907					1·895
0·06	2·17(0)	2·17(0)	2·17(1)	2·17(8)	2·18(1)	2·18(4)				2·16(9)
0·07	2·41(7)	2·41(8)	2·42(1)	2·42(6)	2·42(8)	2·43(2)				2·41(6)
0·08		2·64(6)	2·64(7)	2·65(4)	2·65(6)	2·65(9)				2·64(5)
0·09		2·85(3)	2·85(5)	2·86(0)	2·86(6)	2·86(8)				2·85(2)
0·10			3·05	3·05	3·06	3·06				3·05
0·12			3·38	3·39	3·40	3·40				3·38
0·15				3·82	3·82	3·83	3·83			3·81
0·18				4·17	4·17	4·18	4·19			4·17
0·20					4·38	4·38	4·39			4·37
0·25					4·82	4·82	4·83			4·81
0·3					5·19	5·19	5·20	5·24		5·18
0·4						5·84	5·85	5·86		5·82
0·5						6·42	6·43	6·45		6·41
0·6							6·99	7·00	7·04	6·95
0·7							7·51	7·54	7·56	7·48
0·8							8·02	8·03	8·07	7·98
0·9							8·50	8·53	8·55	8·46
1·0							8·96	8·98	9·01	8·93
1·2							9·84	9·86	9·88	9·80
1·5								11·06	11·10	10·98
1·8								12·18	12·20	12·10
2·0								12·85	12·91	12·77
2·5								14·47	14·50	14·38
3									16·01	15·86
4									18·73	18·59
5									21·2(9)	21·1(3)

It should be emphasized that the corrections made to the values of W' are very small; for each value of $E/p \leqslant 0\cdot5$ the discrepancy between the best estimate and the result taken at the highest pressure is less than $0\cdot25\%$, for $0\cdot5 < E/p \leqslant 1\cdot2$ this discrepancy remains less than $0\cdot5\%$, while for $E/p > 1\cdot2$ it ranges from $0\cdot8$ to $1\cdot2\%$. The fact that corrections made to the measured values of W' for $E/p > 1\cdot2$ are greater than $0\cdot5\%$ is the only reason for the increased error limit placed on these data.

Table 2

D/μ in deuterium at 293°K

E/p	D/μ (V) at p (torr) of:									Average
	500	400	300	200	150	100	40	20	10	
0·006	0·0257(2)									0·0257(2)
0·008	0·0260(2)	0·0259(7)								0·0260(0)
0·010	0·0263(5)	0·0263(5)	0·0263(2)							0·0263(4)
0·015	0·0271(6)	0·0271(8)	0·0271(6)	0·0271(0)						0·0271(5)
0·020	0·0281(2)	0·0281(4)	0·0281(2)	0·0280(6)	0·0279(9)					0·0280(9)
0·025		0·0292(0)	0·0291(5)	0·0291(0)	0·0290(8)					0·0291(3)
0·03			0·0303	0·0302	0·0302	0·0301				0·0302
0·04				0·0326	0·0325	0·0325				0·0325
0·05				0·0350	0·0350	0·0349				0·0350
0·06					0·0376	0·0375				0·0376
0·07					0·0402	0·0400				0·0401
0·08					0·0429	0·0428				0·0429
0·09						0·0456	0·0454			0·0455
0·10						0·0483	0·0482			0·0483
0·12							0·0540			0·0540
0·15							0·0629	0·0627		0·0628
0·18							0·0722	0·0720		0·0721
0·20							0·0785	0·0783		0·0784
0·25							0·0943	0·0942		0·0943
0·3							0·1102	0·1101	0·1094	0·1099
0·4							0·1406	0·1402	0·1399	0·1402
0·5							0·1682	0·1679	0·1670	0·1677
0·6								0·1931	0·1920	0·1926
0·7								0·216(2)	0·215(1)	0·215(7)
0·8								0·237(9)	0·236(2)	0·237(1)
0·9								0·258(5)	0·257(2)	0·257(9)
1·0								0·277(7)	0·276(6)	0·277(2)
1·2								—	0·313	0·313
1·5								0·366	0·364	0·365
1·8								—	0·411	0·411
2·0								0·441	0·440	0·441

The only other results for the drift velocity of electrons in deuterium are those of Pack, Voshall, and Phelps (1962), who used a gas temperature of 300°K. The present results agree with their data at low values of E/N (where N is the gas number density) but appear to diverge by as much as 7% at the higher values of E/N, the magnitude of the discrepancy being masked to some extent by the scatter in their data. The results for hydrogen of Pack and Phelps (1961), who used the same apparatus and experimental technique as Pack, Voshall, and Phelps, show a similar discrepancy when compared with the data of Bradbury and Nielsen (1936) and Lowke (1963), these last two sets of data being in good agreement with one another.

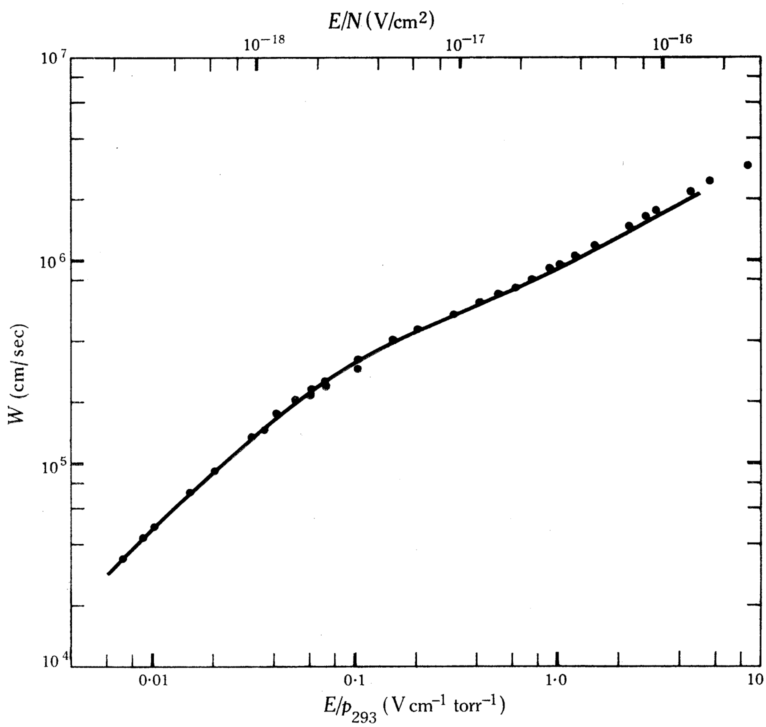

Fig. 1.—Variation of W with E/p_{293} or E/N for electrons in deuterium at 293°K; —— present results, ● Pack, Voshall, and Phelps (300°K).

Figure 1 shows the present results and those of Pack, Voshall, and Phelps plotted as a function of E/p_{293} or E/N. The present results are not plotted individually, since all of the best estimate values are contained within the thickness of the curve. Hall (1955) measured the magnetic deflection drift velocity W_M, which is not the true drift velocity (Huxley 1960; Jory 1965) and therefore no reference to her data is made in Figure 1.

(*b*) *Ratio of Diffusion Coefficient to Mobility*

Results for D/μ are shown in Table 2; an accuracy limit of $\pm 1\%$ is placed on the average values in this table. The entries are the averages of two sets of results taken in the same apparatus but with different collecting electrodes requiring different small compensating potentials; the agreement between these two sets of results was of the order of $0 \cdot 5\%$. The useful parameter k_1 can be obtained from the ratio of diffusion coefficient to mobility by the use of the relation

$$k_1 = (D/\mu)(kT/e)^{-1}, \tag{2}$$

where $\mu = W/E$, k is Boltzmann's constant, T is the temperature, and e is the electronic charge. The slight decrease in the values of D/μ (amounting to a maximum of $0 \cdot 7\%$ at $E/p = 0 \cdot 3$) as the pressure is reduced at a given value of E/p is instrumental in origin and is of the same form as the change expected from the influence of the finite size of the source hole in the apparatus (Crompton and Jory 1962; Crompton, Elford,

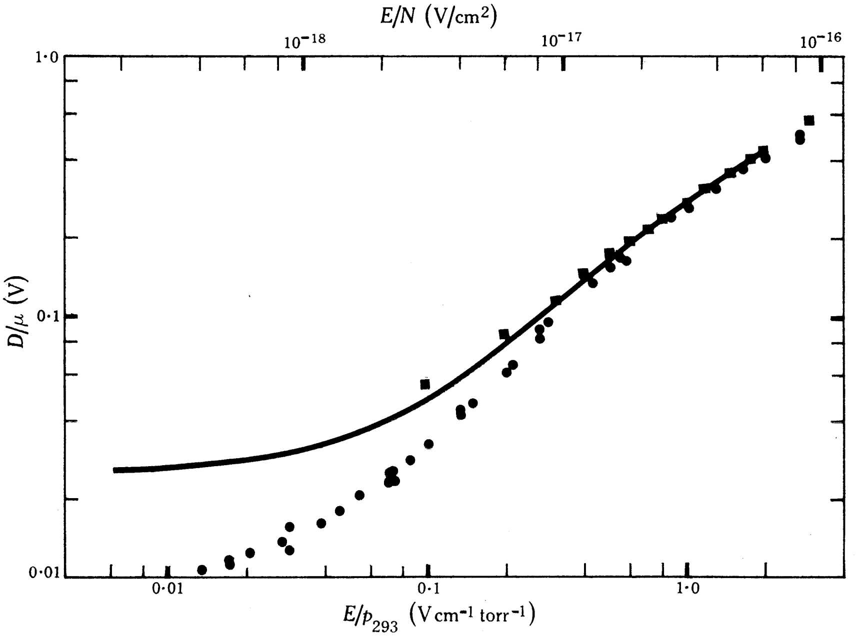

Fig. 2.—Variation of D/μ with E/p_{293} or E/N for electrons in deuterium at 293°K; —— present results, ■ Hall (288°K), ● Warren and Parker (77°K).

and Gascoigne 1965). Crompton and Jory's calculations suggest an upper limit of $0 \cdot 8\%$ for this effect under the present experimental conditions and so the average values in Table 2 should still lie within the claimed accuracy.

The present values of D/μ are plotted in Figure 2; all the 31 average values from the present experiment lie within the thickness of the curve. Also shown in Figure 2 are the data of Hall (1955) and the relevant part of the data of Warren and Parker (1962).

Hall's data are the only other results for deuterium at 293°K, but there is only limited overlap with the present range of E/p. Since Hall used lower gas pressures and did not correct for the effects of contact potential differences in her apparatus, her results are more susceptible to experimental error than are the present ones. Nevertheless, at the highest values of E/p, where the effects of contact potentials are least, the two sets of data agree to within the combined experimental error.

Warren and Parker's results were taken at a gas temperature of approximately 77°K and are therefore directly comparable with the present data only at high values of E/N, where the values of D/μ should become independent of the gas temperature. Their data do, to a large extent, merge with the present data but there is a residual discrepancy of approximately 7% that could be due either to the large scatter in their data, often in excess of 5%, or to the fact that the value of E/N is not sufficiently high for the gas temperature to be unimportant. This phenomenon will be investigated when, using the same apparatus, the present results are extended to 77°K.

IV. Acknowledgments

The author wishes to thank Dr. R. W. Crompton for continuous guidance and the other members of the Ion Diffusion Unit for frequent discussions throughout this work.

The financial assistance of an A.N.U. research scholarship is also gratefully acknowledged.

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