

ELECTRON TRANSPORT COEFFICIENTS IN HYDROGEN AND DEUTERIUM

By R. W. CROMPTON,* M. T. ELFORD,* and A. I. MCINTOSH*†

[Manuscript received August 31, 1967]

Summary

Measurements have been made of the drift velocity W and the ratio of diffusion coefficient to mobility D/μ for low energy electrons in deuterium at 77°K, and of D/μ in hydrogen at 77 and 293°K. Tabulated data are given for D/μ within the range $2 \times 10^{-20} \leq E/N \leq 1.2 \times 10^{-16}$ V cm² and for W within the range $8 \times 10^{-20} \leq E/N \leq 9.5 \times 10^{-17}$ V cm². The low temperature results show a considerably reduced scatter when compared with previously published data and are of an accuracy comparable with the results of recent measurements made at room temperature. The data obtained complement those of Lowke and of McIntosh thus completing a set from which a more accurate determination of low energy elastic and inelastic cross sections can be made.

I. INTRODUCTION

Measurements of the drift velocity W and the ratio of diffusion coefficient to mobility D/μ for electrons moving through a gas under the influence of a uniform electric field have been used for many years to estimate the energy dependence of the momentum transfer cross section for collisions between electrons and gas molecules (see, for example, Crompton and Sutton 1952). Until recently, experiments of this type were subject to considerable experimental error and, moreover, the data obtained from them could be interpreted only in terms of various mean quantities (Crompton and Sutton 1952; Huxley and Crompton 1962). With the use of improved techniques and a better understanding of the factors limiting the accuracy of experiments of this kind, experimental data with an error of less than 1% can now be obtained (Crompton and Jory 1962; Crompton and Elford 1963; Lowke 1963). Furthermore, the use of computers has enabled these data to be analysed to determine the energy dependence of the cross sections for both elastic and inelastic processes without resorting to the less satisfactory averaging procedures. Analyses of this type (Frost and Phelps 1962; Engelhardt and Phelps 1963; Crompton, Elford, and Jory 1967) show that the techniques are capable of yielding results of reasonable energy resolution and therefore, in certain circumstances, allow a direct comparison to be made with the results of single scattering experiments. However, not all of the data on which these analyses have been based have been sufficiently accurate to allow maximum use to be made of the analytical techniques.

* Ion Diffusion Unit, Australian National University, Canberra, A.C.T. 2600.

† Present address: Department of Pure and Applied Physics, Queen's University, Belfast, Northern Ireland.

In the inert gases at energies well below the first excitation threshold it is possible to infer the momentum transfer cross section directly from the experimental data. In such cases the cross section found is unique and its accuracy depends ultimately only on the precision of the experimental data (Crompton, Elford, and Jory 1967). On the other hand, in the molecular gases, where both elastic and inelastic collisions must be taken into account at all energies, the results obtained have been less satisfactory (Frost and Phelps 1962; Engelhardt and Phelps 1963). While this situation is largely due to the difficulties in obtaining a unique set of elastic and inelastic cross sections that are consistent with the experimental data, it may in part be attributed to the inadequacy of some of these data. Since any spread in the data leads to ambiguity in determining the cross sections, it is clearly desirable to achieve the greatest possible accuracy in the experimental measurements.

In experiments of the type described in this paper, the mean electron energy, as well as the distribution of electron energies, is controlled by the electric field strength and the nature, temperature, and number density of the gas. At a given gas temperature, the mean electron energy can be varied by varying E/N , the ratio of the electric field strength to the gas number density. If this ratio is large, the mean electron energy is well above the thermal energy of the gas molecules. On the other hand, if the field strength is small and the gas number density is large the rate at which energy is gained from the field is small while the frequency of the collisions in which excess energy is transferred to the gas molecules is large. In this case the energy balance may be achieved with the mean electron energy exceeding that of the gas molecules by only a few per cent and the electron energy can be controlled by varying the gas temperature.

Although the temperature of the gas may be lowered simply in order to extend the lower energy limit of the experiments, this procedure may have an additional advantage in that the subsequent analysis of the data to determine the cross sections may be simplified. For example, in hydrogen and deuterium at 77°K only the two lowest rotational levels are populated significantly and the electron energy distribution is therefore controlled by the cross sections for momentum transfer and for two rotational transitions only.

The electron transport coefficients measured in the present investigation were the drift velocity W and the ratio of diffusion coefficient to mobility D/μ , since these are the transport coefficients that can be measured with the greatest accuracy using existing techniques (Crompton, Elford, and Jory 1967). The measurements of W were made using the Bradbury-Nielsen method while the measurements of D/μ were made using the Townsend-Huxley lateral diffusion technique. Both types of experiments have been the subject of critical analyses (Crompton and Jory 1962; Lowke 1962; Crompton, Elford, and Gascoigne 1965) and their reliability is well established. Data for D/μ in hydrogen at 293 and 77°K, and for W and D/μ in deuterium at 77°K are contained in the present paper. These data complement the drift velocity data in hydrogen of Lowke (1963) and the data for W and D/μ in deuterium at 293°K of McIntosh (1966). A preliminary account of the measurements of D/μ in hydrogen at 293°K was given by Crompton and Elford (1963).

II. APPARATUS AND EXPERIMENTAL TECHNIQUES

(a) *Lateral Diffusion Experiments*

The method of measuring D/μ has been described in detail elsewhere (e.g. Crompton and Jory 1962) and will be considered only briefly here.

Electrons enter the diffusion chamber through a small hole in the cathode and then drift and diffuse under the influence of the uniform electric field E towards the anode, which is divided into a central disk of radius b and a surrounding annulus. The ratio R of the electron currents received by the segments of the anode is measured. It may be shown (Huxley and Crompton 1955; Crompton and Jory 1962; Hurst and Liley 1965) that the values of D/μ are related to the measured current ratios by the expression

$$R = 1 - (h/d) \exp\{-\lambda(d-h)\}, \quad (1)$$

where h is the distance between the cathode and anode,

$$d^2 = h^2 + b^2, \quad \text{and} \quad 2\lambda = E/(D/\mu).$$

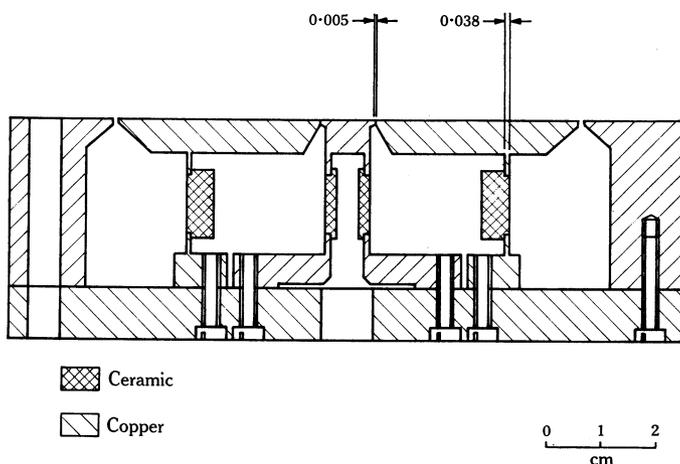


Fig. 1.—Schematic section through the lower electrode assembly of the lateral diffusion apparatus.

The apparatus and some of the experimental details and techniques used in the present investigation have been described in detail by Crompton, Elford, and Gascoigne (1965). The only major change in the apparatus was the replacement of the collecting electrode by one that was suitable for use at 77°K. The earlier collecting electrode, which consisted essentially of a disk and surrounding annulus mounted rigidly on a glass backing plate, proved unsatisfactory below 90°K when differential contraction of the components caused the disk and annulus, separated by an annular gap of 0.005 cm, to touch. In the collecting electrode used for most of the present investigation (see Fig. 1) the disk and annulus are supported by thin-walled copper cylinders 0.3 cm long which are vacuum brazed to concentric ceramic cylinders.

The cylinders are supported on the base plate in a similar way. The success of this design is due to the effectiveness of the copper cylinders, whose wall thickness is only 0.04 cm, in uniformly absorbing the differential contraction between the copper and ceramic components as the electrode is cooled to 77°K, thus ensuring that the disk and annulus do not touch and that the whole electrode remains flat at this temperature. An optical test at both 293 and 77°K showed that the disk and annulus remained undistorted and coplanar over this temperature range. The resistance to ground of each component was greater than 10^{14} ohms.

The experimental equipment used was identical to that described by Crompton, Elford, and Gascoigne. Each experimental observation, made with an accurately known field E established in the diffusion chamber, consisted of the measurement of the gas temperature and pressure together with the ratio R of the currents received by the disk and annulus, each of which was of the order of 10^{-12} A. This information, together with the dimensions of the apparatus, enabled the value of E/N and the corresponding value of D/μ to be determined.

Calculations show that impurity levels of up to 50 p.p.m. have a negligible effect on the measured transport coefficients in hydrogen and deuterium. Experience has shown that the level of impurity as a result of outgassing of the tube can be kept well below this value without baking the apparatus providing the outgassing rate is reduced to an adequate level by evacuating the apparatus for a long period before commencing the experiments. Isolation tests made without using liquid nitrogen traps showed that the rate of rise of pressure was of the order of 5×10^{-6} torr/hr, which corresponds to a gas influx rate of 8×10^{-9} torr litre/sec. The rate of rise of impurity level in a 500 torr sample of gas at 293°K is therefore 1 part in 10^8 per hour.

The hydrogen and deuterium were obtained by diffusion through a silver-palladium alloy osmosis tube using the apparatus and technique described by Crompton and Elford (1962). This method is known to be capable of producing hydrogen with an impurity level of less than 0.1 p.p.m. (Young 1963). The deuterium (from General Dynamics Corporation) contained not less than 99.9% of the isotope. The small amounts of hydrogen and deuterium hydride that may have been admitted by diffusion through the palladium would have a negligible effect on the measured transport coefficients in deuterium.

Two pressure gauges were used: a 0–500 torr capsule gauge of the type described by Crompton and Elford (1957), and a 0–250 torr fused quartz spiral gauge, manufactured by Texas Instruments Ltd. Both gauges were calibrated against a C.E.C. type 6–201 primary pressure standard. Using the capsule gauge the pressure could be measured with an error of less than 1% at 500 torr, the greater part of this error being due to hysteresis effects in the capsule. Fortunately, high pressures are needed only for the measurements at very low values of E/N . In this region D/μ varies slowly with E/N and hence errors in pressure measurement are relatively unimportant. The quartz spiral gauge was used to measure all pressures in the range 5–250 torr with an error of less than 0.1%.

The temperature at which the measurements are made can affect the value of D/μ either directly or indirectly through its effect on the gas number density, since the gas pressure rather than N is measured to determine E/N . An error of 1 degK

leads to an error of 0.3% in N at 293°K and of more than 1% at 77°K, and it is therefore necessary to control the temperature closely and to measure it accurately. For the room temperature experiments the temperature of the laboratory was controlled to ± 1 degK and the heat generated by the filament was removed by a water jacket through which distilled water was circulated by a small pump. At 77°K the apparatus was immersed in a liquid nitrogen bath, the level of the liquid nitrogen being controlled automatically to within 0.5 in. by a device based on the design of Pursar and Richards (1959). For the experiments at both temperatures the gas temperature was measured using two fine-wire copper-constantan thermocouples, one attached to the cathode and the other to the earthed ring surrounding the collecting electrode.

To obtain reproducible calibration values for the thermocouples at 77°K it was found necessary to use fully annealed copper wires. The thermocouples were calibrated against the boiling point of liquid nitrogen, care being taken to ensure that the liquid nitrogen was not super-heating. The purity of the liquid nitrogen was determined and the boiling point corresponding to the atmospheric pressure found. The same calibration values were obtained for many thermocouples prepared from different lengths of the same wire. During the assembly of the apparatus the calibration of the actual thermocouples used was confirmed after their installation in the vacuum envelope. The sensitivity of the thermocouples was approximately $16 \mu\text{V}/\text{deg}$ at 77°K, which, with the potentiometer used, enabled the temperature to be determined to better than 0.2 degK.

A possible source of error in lateral diffusion experiments is the presence of contact potential differences in the chamber (Crompton, Elford, and Gascoigne 1965). Despite the attention given to this problem, small contact potential differences remained in the apparatus, but these were eliminated, or compensated for, by the application of a small potential in the manner described by Crompton, Elford, and Gascoigne. For the measurements at 293°K the value of this potential was adjusted until the observed value of D/μ for K^+ ions was equal to the expected value of kT/e .

(b) Additional Experimental Problems in Lateral Diffusion Experiments at 77°K

When measurements of D/μ were first made at 77°K, several sources of error in addition to those investigated at 293°K were encountered. Although it was not always possible to eliminate these sources of error, methods of overcoming or avoiding them were developed. The investigation of one of these difficulties, the current dependence of the results at low E/N , led to the discovery of the extreme sensitivity of the experiments to oxygen in concentrations several orders of magnitude smaller than the limit of detection of any other known method.

(i) Compensation for Contact Potential Differences

At 77°K it was found that the use of the positive ion test to adjust the contact potential compensation (Crompton, Elford, and Gascoigne 1965) led to large errors in the observed values of D/μ , the errors increasing as the test proceeded. Over a period of several hours, the measured value of D/μ for the positive ions increased by more than 10% from a value that was initially only 1% above the expected value of kT/e . Electron results taken at intervals during the same period showed a similar,

but smaller, increase. It should be noted that this does not correspond to a change in the contact potential differences within the apparatus, since this would have resulted in errors of different signs in the two cases. When measurements were taken only with electrons, i.e. the positive ion test was not used, the values obtained were consistent and did not vary with time. In subsequent experimental runs measurements were taken only with electrons and the compensation for contact potential differences was adjusted until for any given value of E/N the same value of D/μ was obtained when results were taken with a wide range of electric field strengths.

In previous papers (Crompton, Elford, and Gascoigne 1965; McIntosh 1966; Crompton, Elford, and Jory 1967) it has been stated that, to keep errors from contact potential differences within acceptable limits, the lowest value of the electric field strength used should be 3.0 V/cm. In the present apparatus, a stream of near-thermal electrons is not sufficiently divergent at 77°K to allow accurate measurements of the current ratios when field strengths of greater than 2.5 V/cm are used (Crompton, Elford, and Gascoigne 1965) and therefore field strengths of as little as 1.0 V/cm were used to obtain the values of D/μ at values of E/N of the order of 10^{-20} V cm². Provided the compensating potential was correctly adjusted at 293°K with $E = 3.0$ V/cm, and was left at this setting when the apparatus was cooled to 77°K, it was found that errors that could be attributed to contact potential differences were generally less than 0.5% at $E = 1.0$ V/cm. An error of this magnitude would not have been acceptable for the experiments at 293°K, but was less significant at 77°K when other experimental difficulties caused the error limit placed on the final data to be increased to $\pm 2\%$. When errors due to incorrect compensation were observed at low field strengths, only data taken at field strengths sufficiently high to reduce these errors to less than 0.25% were included in the final data.

(ii) *Surface Effects*

After measurements had been taken at high values of E/N at 77°K, the measured values of D/μ at low E/N increased (e.g. by about 3% at $E = 1.0$ V/cm), especially if the measurements at high E/N were not made until several days after cooling the apparatus to 77°K. Although the size of the error did not exactly halve as the value of E was doubled (as would be expected if the error were due to a contact potential difference in the apparatus; Crompton, Elford, and Gascoigne 1965), it did decrease with increasing electric field strength and was always negligible for results taken with $E \geq 10.0$ V/cm. The error could not be eliminated as long as the apparatus was maintained at 77°K, but could be eliminated by warming the apparatus to room temperature for several days before resuming the low temperature measurements. It therefore seems probable that an insulating layer is formed when the somewhat more energetic electrons in the swarm at high E/N bombard an adsorbed layer on the surface of the collecting electrode.

Fortunately, although the effect was inconvenient, it could always be eliminated and the final data were not subject to errors from this source. At low values of E/N , only those results taken when no effect was observed were included in the final data. At higher values of E/N , when larger electric field strengths were used, the values of D/μ were always in agreement whether or not the effect was present. All the data

obtained at high E/N and high field strengths were therefore included in the final analysis.

(iii) *Current Dependence of Results at Low E/N*

Crompton and Elford (1963) reported a slight dependence of the divergence of the electron stream on the total current received by the anode. The same phenomenon occurred in the present experiments. When such a dependence was observed, it was found that the apparent values of D/μ were linearly dependent on the current; the true value of D/μ was therefore found by extrapolating to zero current from values recorded at 1×10^{-12} and 2×10^{-12} A. The difference between the extrapolated value of D/μ and the value recorded at the lowest current was nearly always less than 1% for the room temperature experiments and always decreased rapidly with increasing E/N .

The slope of the D/μ against current graph increased progressively with time for a given gas sample. When a high current dependence was found in a particular sample of gas, a moderately high dependence was found in the next sample used, even though the apparatus was evacuated to a pressure of less than 10^{-6} torr between experimental runs. Both of these effects indicated that the phenomenon was associated with the outgassing of the apparatus, although the level of contamination from this source was known to increase at a rate less than 0.1 p.p.m./hr for a 500 torr sample of gas. The gases most likely to be present from outgassing were oxygen, carbon dioxide, and water vapour. Known proportions of these gases were added to the hydrogen in concentrations of a few p.p.m. In other tests carried out at room temperature, small amounts of the solvents used during the assembly of the apparatus (hexane, acetone, and isopropyl alcohol) and excessive amounts of the tap grease and the wax used for the demountable seal of the apparatus were also added. With the exception of the oxygen, all of the impurities added produced no observable current dependence of the results. In the case of oxygen, the slope of the D/μ against current curve was approximately linearly dependent on the amount of oxygen added.

Since attachment of thermal electrons to oxygen is known to be appreciable (Chanin, Phelps, and Biondi 1962), it was suggested that negative ions were present in the electron stream and that these ions led to space charge repulsion. At sufficiently low values of E/N , both the ions and the electrons are in thermal equilibrium with the gas and therefore the current distribution at the anode is the same for both species. Thus, if space charge effects were negligible, the current ratios would not be affected by the presence of a small number of negative ions in the stream and there would be no current dependence of the results. On the other hand, if space charge repulsion does affect the stream, a small number of ions will have a large effect, since, at low E/N , their drift velocity is of the order of 1000 times smaller than the corresponding drift velocity of electrons.

In the experiments at 77°K, the current dependence was found to be about five times greater than it had been at 293°K and to increase as the gas number density N increased. The increase with N can be qualitatively explained in terms of the hypothesis proposed above. For a given value of the electric field strength E , as N is increased the effective E/N is decreased and the drift velocities of the electrons

and ions decrease; thus, for a given attachment rate, the effect of space charge on the stream is increased. Secondly, since the attachment of thermal electrons to oxygen is a three-body process, the rate of attachment depends on the square of the number density; an increase in N again leads to a larger current dependence.

Although the current dependence of the results at low E/N could be reasonably explained in terms of space charge repulsion enhanced by the presence of negative ions, the proportion of oxygen molecules present in the experiments at 77°K was expected to be very much less than 0.1 p.p.m. (see Section II(a)) owing to the reduced outgassing rate, so that some doubt was cast on the validity of the explanation. To confirm that such a small proportion of oxygen could lead to the large effects observed, mixtures of known concentrations of oxygen in hydrogen were made and the current dependence in these mixtures examined.

Mixtures with oxygen concentrations ranging from 0.5 p.p.m. to 3 parts in 10^{10} were prepared. In the most contaminated of these mixtures (0.5 p.p.m. of oxygen) the current ratio was immeasurably small, i.e. the space charge repulsion in the stream was so great that only a negligible fraction of the electron current fell on the central disk of 1 cm diameter. In the mixture containing 3 parts in 10^{10} of oxygen, the current dependence of the results approached, but was still greater than, that observed in the normal experimental runs.

The data obtained in these deliberately contaminated gas samples is in semi-quantitative agreement with the theory of Liley (1967), a more exact comparison being difficult in view of the uncertainty of some of the quantities required for the calculations.

Since the experimental conditions at 293°K could always be arranged to ensure that the difference between the extrapolated value of D/μ and the value measured at the lowest current was less than 1%, no attempt was made to reduce the oxygen content of the gas samples. After prolonged periods of pumping the difference was often reduced to as little as 0.25% at $E/N = 2 \times 10^{-19}$ V cm² and was too small to detect at higher values of E/N . All the 293°K data presented in Section III(a) were obtained under these conditions. Although the current dependence at 77°K was considerably larger, any errors incurred by the extrapolation of the values of D/μ to zero current were negligible compared with the errors from other sources.

(c) *Drift Velocity Experiments*

The method used to measure the electron drift velocities, that of Bradbury and Nielsen (Nielsen 1936), has been described by Lowke (1963). The apparatus used in the present investigation maintains the essential features of the one described by Crompton, Elford, and Jory (1967), but differs from their apparatus in several important details.

The present apparatus was designed primarily for the measurement of electron drift velocities in ultra-pure gases at low temperatures. The drift tube was therefore made as small as possible and was constructed in a form suitable for relatively high temperature baking to achieve the required low outgassing rates. These re-

restrictions made it difficult to use the guard electrode structure used in the apparatus of Crompton, Elford, and Jory and in the lateral diffusion apparatus described in Section II(a), and also made it impossible to use a demountable seal as had been done in both of the earlier apparatuses.

The form of the guard electrode structure used can be seen in Figure 2. The electrodes, machined from copper and lapped and polished to a high degree of flatness and surface finish, were separated by ground glass spacers and mounted on ceramic tie-rods. Field plots for the electrode structure showed that a field which was virtually free of distortion over the important central region could be produced and that the system effectively prevented field distortion within the chamber from external sources.

A comparison of results obtained using the present apparatus with those obtained using the drift velocity apparatus of Crompton, Elford, and Jory, which was known to yield highly accurate data, showed that there was a systematic error of approximately 0.3% in the present apparatus. If the distance between the planes of the shutters was taken to be 5.014 cm instead of the measured value of 5.008 cm, the agreement between the two sets of data was to within 0.2% for all electric field strengths greater than 8.0 V/cm. The empirical distance was used in subsequent measurements and no further discrepancies between the measured values and the results of Crompton, Elford, and Jory or Lowke (1963) were observed.

The shutters were constructed of 0.08 mm diameter nichrome wires separated by 0.4 mm and sealed under tension on ceramic rings of internal and external diameters 3.0 and 5.5 cm respectively.

Figure 2 shows the apparatus mounted inside the Pyrex glass envelope. Kovar tube seals were used to bring the electrical leads through the glass. Unlike the lateral diffusion apparatus described above, the entire apparatus was immersed in liquid nitrogen to a depth just above the bottom of the glass skirt on the filament stem (see Fig. 2). Total immersion of the apparatus reduced the pressure variations caused by oscillations in the level of the refrigerant and also helped to reduce the temperature gradient between the top and bottom of the apparatus. The electrical leads through the glass skirt were sealed with silicon rubber, thereby ensuring that the space between the filament stem and the glass skirt was sealed off from the atmosphere. This arrangement prevented condensation and ice formation on the leads.

The potentials applied to the electrodes of the drift tube were similar in accuracy and stability to those applied to the lateral diffusion apparatus. The voltage between the planes of the electrode shutters was measured to within 0.05%.

The determinations of the frequencies of the maxima in the current-frequency curves were made using the equipment and techniques described by Elford (1966). The vacuum and gas handling techniques were essentially similar to those used in

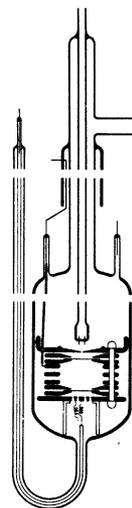


Fig. 2.—Drift tube.

the lateral diffusion experiments, but the rate of rise of pressure in the drift tube was at least four times smaller than in the lateral diffusion apparatus.

Unlike the ratio of diffusion coefficient to mobility, the drift velocity is strongly dependent on E/N even at very small values of this parameter. As a result, the gas pressure must be measured as accurately as possible over the entire pressure range. To obtain the desired accuracy it was therefore necessary to use the quartz spiral gauge for the measurement of all pressures. Since this instrument is essentially a null manometer with a range of a little over 250 torr, pressures in the range 250–500 torr were measured by operating the gauge with its reference pressure held accurately at 250 torr. Stability of the pressure in the reference volume was improved by the addition of a 5 litre ballast volume immersed in a water bath.

The single thermocouple in the drift tube was attached to the electrode adjacent to the top shutter. Since the lower half of the apparatus was in good thermal contact with the liquid nitrogen bath, the existence of any temperature gradients could still be detected using this thermocouple, provided it was assumed that the lower end of the apparatus was at the bath temperature. Only very small temperature gradients were observed, the details of which are given in Section III(c) below. The thermocouple was prepared and calibrated and its e.m.f. measured in the manner described above.

Lowke (1963) showed that the measured drift velocities in a Bradbury–Nielsen experiment are relatively insensitive to distortion of the electric field. The primary effect of contact potential differences within the drift chamber is therefore to falsify the total potential difference between the planes of the shutters. The shutter wires were gold coated by vacuum deposition to minimize errors from this source, but in the present apparatus it was not considered necessary to coat the whole interior with gold. The results presented below show no effects of contact potential differences when the electric field strength is 8.0 V/cm or greater.

Each experimental observation consisted of the determination of the transit time of the electron pulse and the temperature and pressure of the gas. These data, together with the electric field strength and the distance between the shutters, enable the value of W and the corresponding value of E/N to be calculated.

III. RESULTS

(a) *Values of D/μ in Hydrogen at 293°K*

In the experiments at 293°K both the gas pressure and temperature could be accurately controlled. It was therefore possible to measure the value of D/μ at predetermined values of E/N corresponding to values of E/p_{293} (p is the gas pressure) chosen to facilitate comparison with earlier work, and no corrections resulting from departures of the actual values of E/N from the chosen values were necessary.

Results were taken using the collecting electrode and experimental techniques described by Crompton, Elford, and Gascoigne (1965) and with the collecting electrode and techniques described in Section II(a). These two sets of data were in agreement with each other to within 0.5% and their averages are presented in the final column of Table 1. An error limit of $\pm 1\%$ is placed on the average values in this table.

(b) Values of D/μ in Hydrogen and Deuterium at 77.3°K

A temperature gradient of approximately 0.3 degK appeared between the cathode and anode of the diffusion chamber as the pressure was lowered from 500 to 5 torr over a period of several hours. A corresponding change in the mean temperature of the apparatus from 77.3 to 77.4°K was observed. This temperature rise results from the fact that the top section of the apparatus becomes less effectively coupled

TABLE I
EXPERIMENTAL VALUES OF D/μ FOR ELECTRONS IN HYDROGEN AT 293°K

$10^{17} E/N$ (V cm^2)	E/p_{293} ($\text{V cm}^{-1} \text{ torr}^{-1}$)	D/μ (volt) at p (torr) of:						Average
		500	400	300	200	150	100	
0.01821	0.006	0.0258(1)						0.0258(1)
0.02428	0.008	0.0261(7)	0.0261(6)					0.0261(7)
0.03035	0.010	0.0265(3)	0.0265(1)	0.0265(0)				0.0265(1)
0.04553	0.015	0.0275(1)	0.0275(2)	0.0275(1)	0.0274(2)			0.0274(9)
0.06071	0.020	0.0286(1)	0.0285(8)	0.0285(9)	0.0285(2)	0.0284(7)		0.0285(5)
0.07589	0.025		0.0297(3)	0.0297(1)	0.0296(6)	0.0296(2)		0.0296(8)
0.09106	0.03			0.0308	0.0308	0.0308	0.0307	0.0308
0.1214	0.04				0.0330	0.0330	0.0330	0.0330
0.1518	0.05				0.0352	0.0353	0.0353	0.0353
0.1821	0.06					0.0374	0.0375	0.0375
0.2125	0.07					0.0396	0.0396	0.0396
0.2428	0.08					0.0418	0.0418	0.0418
0.2732	0.09						0.0439	0.0439
		$p = 100$	40	20	10			
0.3035	0.10	0.0461	0.0458					0.0459
0.3643	0.12		0.0500					0.0500
0.4553	0.15		0.0563	0.0561				0.0562
0.5464	0.18		0.0620	0.0621				0.0625
0.6071	0.20		0.0671	0.0664				0.0668
0.7589	0.25		0.0781	0.0776				0.0779
0.9106	0.3		0.0892	0.0884	0.0887			0.0888
1.214	0.4		0.1116	0.1109	0.1111			0.1112
1.518	0.5		0.1338	0.1331	0.1334			0.1334
1.821	0.6			0.1548	0.1554			0.1551
2.125	0.7			0.1758	0.1763			0.1761
2.428	0.8			0.1960	0.1963			0.1962
2.732	0.9			0.215(0)	0.215(0)			0.215(0)
3.035	1.0			0.232(9)	0.232(9)			0.232(9)
3.643	1.2				0.266(5)			0.266(5)
4.553	1.5				0.310			0.310
5.464	1.8				0.350			0.350
6.071	2.0				0.374			0.374

thermally to the liquid nitrogen bath as the gas pressure is decreased. The temperature rise was taken into account in its effect on the value of E/N , but no corrections were made for the direct influence on the values of D/μ .

As described in Section II(a), each experimental observation resulted in a value of E/N and a corresponding value of D/μ . With the exception of data excluded for the reasons given in Section II(b), the results for hydrogen were plotted on a graph with scales sufficiently large to allow the values of D/μ to be read off at the required values of E/N with an error of no more than 0.3% . Almost 250 individual data points fairly evenly distributed over the whole range of E/N were plotted and

every point lay within $\pm 1\%$ of the line of best fit drawn through the data. The results obtained in this manner are given in Table 2 and are considered to be in error by no more than $\pm 2\%$.

A similar procedure was followed with the raw data for deuterium. Almost 300 individual data points were plotted and only three of these did not lie within $\pm 1\%$ of the line of best fit drawn through the remainder. The values of D/μ read from

TABLE 2
EXPERIMENTAL VALUES OF D/μ FOR ELECTRONS IN HYDROGEN AT 77.3°K

E/N (V cm^2)	D/μ (V)						
2.0×10^{-20}	0.00676	2.0×10^{-19}	0.00986	2.0×10^{-18}	0.0294	2.0×10^{-17}	0.159(5)
2.5	0.00681	2.5	0.0108(4)	2.5	0.0329	2.5	0.192(9)
3.0	0.00685	3.0	0.0117(9)	3.0	0.0364	3.0	0.224
3.5	0.00690	3.5	0.0126(8)	3.5	0.0398	3.5	0.252
4.0	0.00696	4.0	0.0135(3)	4.0	0.0433	4.0	0.278
4.5	0.00702	4.5	0.0143(2)	4.5	0.0467	4.5	0.302
5.0	0.00709	5.0	0.0150(8)	5.0	0.0502	5.0	0.325
6.0	0.00723	6.0	0.0164(9)	6.0	0.0572	6.0	0.366
7.0	0.00738	7.0	0.0177(7)	7.0	0.0642	7.0	0.405
8.0	0.00755	8.0	0.0189(3)	8.0	0.0713	8.0	0.440
9.0	0.00772	9.0	0.0200	9.0	0.0786	9.0	0.474
1×10^{-19}	0.00790	1.0×10^{-18}	0.0210	1.0×10^{-17}	0.0860	1.0×10^{-16}	0.506
1.2	0.00827	1.2	0.0229	1.2	0.100(8)	1.2	0.565
1.4	0.00867	1.4	0.0247	1.4	0.115(7)		
1.6	0.00907	1.6	0.0263	1.6	0.130(6)		
1.8	0.00946	1.8	0.0278	1.8	0.145(3)		

this graph at the required values of E/N are shown in Table 3. An error limit of $\pm 2\%$ is placed on the data in this table.

The raw data in both hydrogen and deuterium showed some evidence of a plateau in the D/μ against E/N curve at about $E/N = 2.5 \times 10^{-20} \text{ V cm}^2$, but since the maximum divergence from the smooth curves drawn through the data points given in Tables 2 and 3 was only 0.5% for hydrogen and 0.8% for deuterium, no firm conclusions about the existence of the plateau could be reached.

(c) Values of W in Deuterium at 77.0°K

In the Bradbury-Nielsen method of measuring drift velocities a graph of the transmitted current as a function of the frequency applied to the shutters, shows a series of maxima and minima whose amplitude decreases with increasing frequency. At constant E/N these 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 determination of the transit time, the frequencies corresponding to the first two maxima were determined. In the results presented below, the two values of f_0 obtained in this way were always in agreement with each other to within

0.2%; in about 90% of the observations the agreement was to within 0.1%. The cases where the agreement was not to within 0.1% were in either of two categories:

- (1) at the lowest values of E/N , where the current was small and electrometer noise made accurate estimation of the current peaks more difficult, or
- (2) at the lowest pressures used when the current pulses were greatly broadened by the effects of diffusion.

TABLE 3
EXPERIMENTAL VALUES OF D/μ FOR ELECTRONS IN DEUTERIUM AT 77.3°K

E/N (V cm ²)	D/μ (V)						
2.0×10^{-20}	0.00680	2.0×10^{-19}	0.00866	2.0×10^{-18}	0.0234	2.0×10^{-17}	0.199(7)
2.5	0.00682	2.5	0.00916	2.5	0.0278	2.5	0.237
3.0	0.00685	3.0	0.00962	3.0	0.0323	3.0	0.270
3.5	0.00688	3.5	0.0100(7)	3.5	0.0371	3.5	0.302
4.0	0.00692	4.0	0.0104(9)	4.0	0.0421	4.0	0.331
4.5	0.00697	4.5	0.0109(0)	4.5	0.0471	4.5	0.358
5.0	0.00702	5.0	0.0113(1)	5.0	0.0521	5.0	0.385
6.0	0.00712	6.0	0.0121(1)	6.0	0.0627	6.0	0.435
7.0	0.00722	7.0	0.0128(9)	7.0	0.0737	7.0	0.484
8.0	0.00733	8.0	0.0136(6)	8.0	0.0848	8.0	0.527
9.0	0.00744	9.0	0.0144(3)	9.0	0.0957	9.0	0.570
1.0×10^{-19}	0.00756	1.0×10^{-18}	0.0152(1)	1.0×10^{-17}	0.106(6)	1.0×10^{-16}	0.612
1.2	0.00778	1.2	0.0168(1)	1.2	0.127(9)	1.2	0.694
1.4	0.00801	1.4	0.0184(0)	1.4	0.147(6)		
1.6	0.00824	1.6	0.0200	1.6	0.166(2)		
1.8	0.00846	1.8	0.0217	1.8	0.183(6)		

When the apparatus was filled with gas to a high pressure and cooled to 77°K, the thermocouple attached to the electrode adjacent to the top shutter agreed with the liquid nitrogen bath temperature to within 0.1 degK. At all pressures in excess of 100 torr, the temperature rise as recorded by the thermocouple was negligible; at pressures of 50 torr and below, a temperature rise of as much as 1 degK was observed. This temperature rise results from heating of the gas by the filament and is greater in the drift tube than in the lateral diffusion apparatus because the open structure of the drift tube is less effective in thermally coupling the apparatus to the liquid nitrogen bath.

For the data given below it was assumed that the lower half of the apparatus was always maintained at the temperature of the liquid nitrogen, an assumption that was reasonable in the light of experience gained with the D/μ apparatus. The gas temperature used to calculate the values of E/N was therefore taken to be the average of this temperature and the temperature recorded by the thermocouple. On the other hand the temperature to which the drift data refer may be taken as 77.0°K throughout. For pressures greater than 100 torr the deviations from this temperature were less than 0.15 degK, i.e. the temperature fluctuations were small during the measurement of those values of W that are appreciably temperature dependent. Although deviations

of the mean temperature of as much as 0.5 degK were observed at 20, 10, and 5 torr, the values of E/N used at these pressures were sufficiently high for W to be substantially independent of the gas temperature. Thus, provided the correct temperature was used to calculate the values of E/N , no significant errors were introduced by these more significant departures from the standard temperature.

Three experimental runs were made in deuterium, the measurements of W being made at predetermined values of E/N . Deviations of the actual values of E/N from the chosen values were always less than 1%, most being less than 0.5%. As a consequence of the small pressure-dependent diffusion error (see below), it is not possible to obtain a curve of best fit to represent the data simply by plotting all the experimental points. As described above, this procedure was followed for the D/μ data, since there is no corresponding difficulty in this case. In order to make a correct comparison of the drift data, on the other hand, it is necessary to present the raw data as a function of both E/N and N as in Table 4. This has been effected by applying to each observed value W' the appropriate small correction arising from the departure of the actual value of E/N from the nominal value, thereby obtaining the values of W' corresponding to the values of E/N in the table.

Results obtained at $E = 3.0$ V/cm showed variations of as much as $\pm 0.75\%$, whereas the experimental scatter at high values of E was only 0.2%. It was concluded that the scatter at low field strengths was due to variations in the contact potential differences within the chamber; results taken with field strengths less than 5.0 V/cm were therefore not included in the final table of results.

Lowke (1962) investigated the effects of diffusion on drift velocity measurements and found that the observed drift velocity W' was related to the true drift velocity W through the relation

$$W' = W\{1 + C/(hW/D)\}, \quad (2)$$

in which h is the distance between the planes of the shutters. The constant C depends on a number of factors including the mode of operation of the shutters, the ratio of the shutter open time to the transit time, and the relative sizes of the source and the collecting electrode (Burch, in preparation). It has been found (Elford 1966; Crompton, Elford, and Jory 1967) that the results are generally consistent with a value of C of 1.5 and this is the value used throughout the present investigation.

The measured values W' are shown in Table 4.* Each entry is the average of at least two results differing by no more than 0.3%, a large proportion of the differences between the sets of results being only 0.1–0.2%. The "best estimate" values of W in Table 4 were obtained by applying the correction implied by equation (2) and weighting the results in favour of those taken at higher pressures (Elford 1966; Crompton, Elford, and Jory 1967). The corrections made were less than 0.2% for $3.985 \times 10^{-18} \leq E/N \leq 3.985 \times 10^{-17}$ V cm² and less than 0.35% at higher values of E/N . An error limit of $\pm 2\%$ is placed on the best estimate values in Table 4. This limit is conservative but takes account of uncertainty in the gas number density arising from the temperature rise at lower pressures described above.

* Allowance was made for a reduction of 0.1% in the drift distance due to contraction at 77°K.

Below $E/N = 3.985 \times 10^{-18}$ V cm² the values of W' increase more rapidly as the pressure is lowered than can be accounted for by the influence of diffusion, and consequently no best estimate values of W are given. For example, the increase in W' at $E/N = 9.564 \times 10^{-19}$ V cm² ($\sim 1.5\%$) is more than 10 times greater than that

TABLE 4
EXPERIMENTAL VALUES OF DRIFT VELOCITY FOR ELECTRONS IN DEUTERIUM AT 77°K

E/N (V cm ²)	W' (cm/sec) at p (torr) of:						Best Estimate, W (cm/sec)
	500	400	300	200	100	50	
7.970×10^{-20}	$2.69(7) \times 10^4$						
9.564	3.19						
1.195×10^{-19}	3.90	3.91×10^4					
1.435	4.58	4.58	4.61×10^4				
1.594	5.01	5.02	5.04				
1.992	6.07	6.07	6.09	6.14×10^4			
2.391	7.07	7.08	7.10	7.16			
3.188	8.95	8.97	9.00	9.06			
3.985	1.072×10^5	1.072×10^5	1.077×10^5	1.083×10^5	1.090×10^5		
4.782	1.237	1.239	1.243	1.250		1.257	
5.579	1.393	1.395	1.400	1.407	1.414		
6.376	1.540	1.543	1.548	1.555	1.563		
7.173	1.681	1.682	1.687	1.697	1.704		
7.970	1.814	1.816	1.820	1.831	1.838	1.846×10^5	
9.564	2.06(1)	2.06(2)	2.06(7)	2.07(6)	2.08(5)	2.09(4)	
1.195×10^{-18}		2.39(1)	2.39(6)	2.40(6)	2.41(5)	2.42(4)	
1.435			2.69(5)	2.69(5)	2.70(4)	2.71(4)	
1.594			2.86(0)	2.86(5)	2.87(6)	2.88(7)	
	$p = 200$	100	50	20	10	5	
1.992	3.25×10^5	3.25×10^5	3.26×10^5	3.29×10^5			
2.391	3.56	3.57	3.58	3.59			
3.188		4.06	4.07	4.08			
3.985		4.43	4.44	4.45	4.46×10^5		
4.782		4.72	4.73	4.74	4.74		4.72×10^5
5.579			4.96	4.97	4.98		4.96
6.376			5.16	5.17	5.19		5.16
7.173			5.34	5.35	5.36		5.34
7.970			5.50	5.51	5.52		5.50
9.564			5.79	5.79	5.81		5.78
1.195×10^{-17}				6.20	6.21		6.19
1.435				6.59	6.61		6.58
1.594				6.85	6.87		6.84
1.992				7.51	7.52	7.54	7.50
2.391				8.15	8.16	8.19	8.14
3.188					9.36	9.39	9.34
3.985					1.044×10^6	1.047×10^6	1.042×10^6
4.782					1.146	1.148	1.144
5.579						1.244	1.240
6.376						1.331	1.326
7.173						1.416	1.411
7.970						1.497	1.492
9.564						1.651	1.646

expected from the effects of diffusion. Similar behaviour, but on a larger scale, was observed by Lowke (1963) in his measurements in nitrogen at 77.6°K. However, Lowke did not observe any unexpected pressure dependence of his results in hydrogen at low temperature. To check that the pressure dependence in deuterium was genuine and not instrumental, results were taken in hydrogen at $E/N = 7.970 \times 10^{-19}$ V cm²

and 9.565×10^{-19} V cm² over the same range of pressures as in deuterium. These were in good agreement with those of Lowke (1963), but once again W' was found to increase more rapidly with decreasing pressure than could be accounted for by diffusion. However, at $E/N = 7.970 \times 10^{-19}$ V cm², the increase was only three times that predicted by equation (2) and, since the discrepancy not accountable for by diffusion was only 0.5%, it is doubtful that Lowke, using a smaller range of pressures and less accurate pressure gauges, would have detected so small a difference. If account is taken of the non-ideal behaviour of hydrogen and deuterium, the unexplained discrepancies are reduced by no more than 0.1–0.2%.

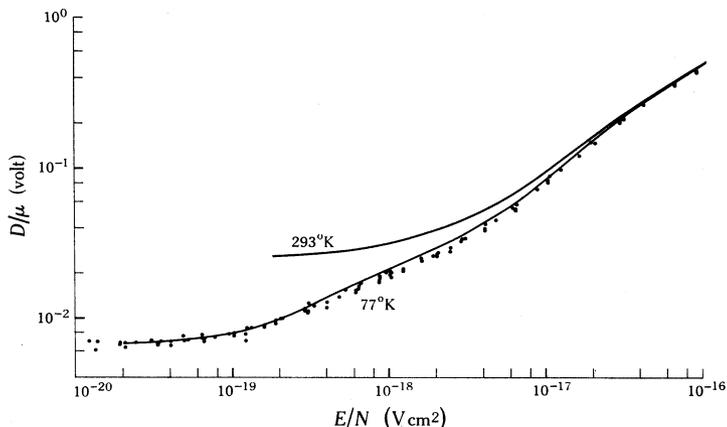


Fig. 3.—Variation of D/μ with E/N for electrons in hydrogen at 77 and 293°K: — present results; ● Warren and Parker.

IV. DISCUSSION

Other results for the values of D/μ in hydrogen have been reported by Townsend and Bailey (1921), Crompton and Sutton (1952), Cochran and Forrester (1962), Crompton and Jory (1962), and Crompton and Elford (1963). Warren and Parker (1962) have reported values of D/μ in hydrogen at 77°K.

With the exception of Crompton and Elford, whose results were presented only in a graphical form, none of the other workers have obtained accurate values of D/μ in the near thermal region. The agreement with Crompton and Elford's results is to within 0.5% over the common range of E/N ($1.82 \times 10^{-19} \leq E/N \leq 3.03 \times 10^{-18}$ V cm² corresponding to $0.006 \leq E/p_{293} \leq 0.100$ V cm⁻¹ torr⁻¹). The agreement with the results of Crompton and Jory (1962) is well within the combined experimental error.* If a temperature of 15°C is assumed for the work of Townsend and Bailey (1921), their results are also in fair agreement with the present data. Above $E/N = 3.03 \times 10^{-17}$ V cm² ($E/p_{293} = 1.0$ V cm⁻¹ torr⁻¹) there is also fair agreement with the results of Crompton and Sutton (1952). The possible sources of error in Crompton and Sutton's data below this value of E/N and the large discrepancy between the data of Cochran and Forrester (1962) and the remaining sets of data have been discussed by Crompton and Jory (1962).

* A small correction must be made to the data of these workers. This correction results from the 0.37% difference between the torr and the 20°C mmHg used by them.

In Figure 3 the present results in hydrogen at 77°K are compared with those of Warren and Parker (1962), the only other data available for this temperature. All the present experimental points lie within the thickness of the plotted lines. Warren and Parker made no compensation for contact potential differences within their apparatus and used field strengths which, at times, were as little as one-tenth of the smallest used in the present experiments. Thus it would be expected that errors from contact potential differences and other surface effects would be much larger in their results than they are in the present results. The lack of self-consistency of Warren and Parker's data forced them to use an empirical calibration of the apparatus to obtain meaningful results. Even with this calibration, the scatter in the tabulated data supplied by them is still often in excess of 5% and the agreement with the

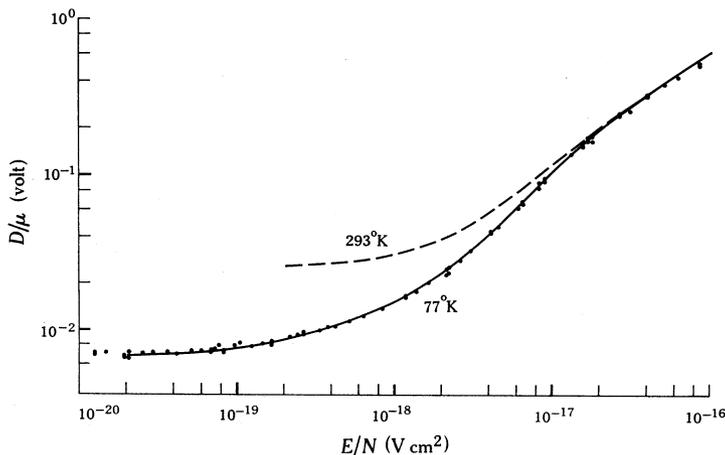


Fig. 4.—Variation of D/μ with E/N for electrons in deuterium at 77°K: — present results; ● Warren and Parker; --- McIntosh (293°K).

present data is only to within 15–20%. By using low electric field strengths Warren and Parker extended their data to values of E/N approximately an order of magnitude lower than the present results. However, the scatter in their data at these very low values of E/N , and the fact that the present data extend to mean energies that exceed thermal energy by less than 2%, suggest that such a step is neither justified nor essential.

A comparison between the values of D/μ measured at 293 and 77°K is also shown in Figure 3. As expected, the curves at both temperatures extrapolate to the corresponding thermal values of kT/e . As E/N is increased, the energy supplied by the field increases and the effect of the thermal motion of the gas molecules becomes less important. Thus the D/μ curves at the two temperatures gradually merge and the value of D/μ is virtually independent of the gas temperature for $E/N > 4 \times 10^{-17}$ V cm².

The present results for D/μ in deuterium at 77°K are shown in Figure 4. This figure also shows a comparison with the 77°K data of Warren and Parker (1962) and the 293°K data of McIntosh (1966). From the figure it can be seen that the agreement between Warren and Parker's data for deuterium and the present results is

considerably better than the corresponding agreement for the hydrogen data, although the scatter in Warren and Parker's data is often in excess of 5%. As in hydrogen, the values of D/μ at the two temperatures gradually merge and the value of D/μ is virtually independent of the gas temperature for $E/N > 4 \times 10^{-17}$ V cm².

The only other results for the drift velocity of electrons in deuterium at 77°K are those of Pack, Voshall, and Phelps (1962). A comparison of the present results with their data and with the 293°K data of McIntosh (1966) is shown in Figure 5. The individual data points for the present 77°K data are not shown since they all lie within the thickness of the plotted line. On the log-log graph shown, the observed pressure dependence below $E/N = 3.985 \times 10^{-18}$ V cm² cannot be seen. The agreement between the present results and those of Pack, Voshall, and Phelps is only fair;

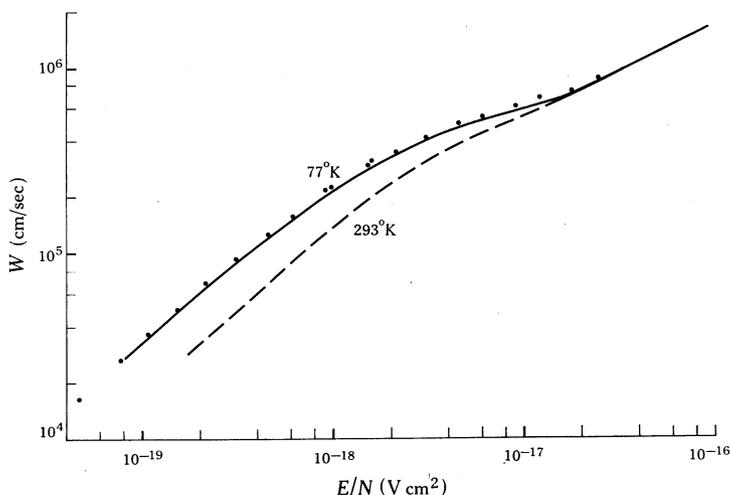


Fig. 5.—Electron drift velocities in deuterium at 77°K: — present results; ● Pack, Voshall, and Phelps; --- McIntosh (293°K).

their values are approximately 7% above the present data over the whole range of E/N studied. The values of W are independent of temperature for $E/N > 4 \times 10^{-17}$ V cm², this observation agreeing well with the temperature independence of the values of D/μ noted in Figure 5.

A comparison of the values of W and D/μ in hydrogen and deuterium at 77°K is shown in Figure 6. The values of the drift velocities in hydrogen are those of Lowke (1963). From the figure it is seen that:

- (1) significant differences between the drift velocities in the two gases appear only for values of E/N greater than the value at which the values of D/μ depart significantly from each other and from the thermal value,
- (2) the drift velocity curves for hydrogen and deuterium cross at very nearly the same value of E/N as that at which the D/μ curves cross, and
- (3) the fractional differences between the values of W in the two gases are about half those between the values of D/μ at the same value of E/N .

Since the momentum transfer cross section is the same in the two gases, the drift velocity would be expected to be the same in those situations in which the energy distribution functions in the two gases are the same. This situation is realized in the thermal region; the agreement between the measured drift velocities for E/N less than about 10^{-19} V cm² thus provides confirmation of the self-consistency of the measurements in the two gases.

The second and third results can be accounted for as follows. For the case of constant momentum transfer cross section q_m , it can be shown (e.g. Crompton, Elford, and Jory 1967, equation (A9)) that

$$W = \frac{1}{3}(2e/m)^{\frac{1}{2}} F(E/N)/q_m (D/\mu)^{\frac{1}{2}}. \quad (3)$$

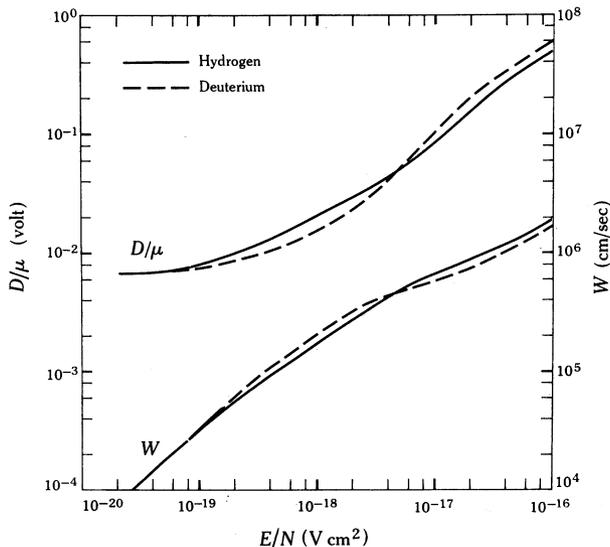


Fig. 6.—A comparison of the variation of W and D/μ with E/N for electrons in hydrogen and deuterium at 77°K.

In this formula e and m are the electronic charge and mass and the factor F is a dimensionless quantity, close to unity, which depends only on the functional form of the energy distribution but is not particularly sensitive to that form. For example, F differs by less than 5% for the Maxwellian and Druyvesteyn distributions. Frost and Phelps (1962) found that their calculated energy distribution functions in hydrogen were intermediate between the Maxwellian and Druyvesteyn forms over the important range of energy, despite the fact that their calculations were carried out over a range of values of D/μ in which the various inelastic processes would assume different degrees of importance. It may therefore be inferred that the energy distributions in hydrogen and deuterium are similar when the values of D/μ are equal, notwithstanding the differences between the inelastic cross sections in the two gases. It follows that, since hydrogen and deuterium have the same, slowly varying, momentum transfer cross section, the values of W should be approximately equal in the two gases for those values of E/N for which D/μ is the same. Furthermore,

since the functional forms of the energy distributions never differ greatly, equation (3) shows that, for any value of E/N , the fractional difference between the drift velocities in the two gases should be half the fractional difference between the corresponding values of D/μ . Figure 6 shows that the experimental results are consistent with these conclusions.

The relatively simple situation that exists in hydrogen and deuterium at 77°K makes it possible to give a qualitative explanation of the shape of the curves in Figure 6. It may be shown (e.g. Farkas 1935) that the percentage populations of the rotational levels in these gases at 77°K are:

	$J = 0$	1	2	3
Hydrogen	24.9%	75.0%	0.1%	—
Deuterium	57.2%	33.1%	9.5%	0.3%

in which J is the rotational quantum number. The threshold for each of the rotational transitions in which J changes by $+2$ is given by (e.g. Gerjuoy and Stein 1955) $(4J+6)B_0$, where B_0 is the rotational constant of the molecule ($B_0 = 0.00754$ eV for hydrogen and 0.00377 eV for deuterium; Herzberg 1950). The thresholds for the $J = 0 \rightarrow 2$ and the $J = 1 \rightarrow 3$ transitions are thus 0.045 and 0.075 eV for hydrogen and 0.023 and 0.038 eV for deuterium.

From Figure 6 it can be seen that the value of D/μ rises initially more rapidly in hydrogen than it does in deuterium. In deuterium the threshold for the first rotational transition is sufficiently low that, even when the electrons are in thermal equilibrium with the gas molecules, there are a significant number with sufficient energy to cause rotational excitation. Since almost 60% of the deuterium molecules occupy the $J = 0$ level, most of the additional energy received by the electrons as E/N is increased is used in exciting the $J = 0 \rightarrow 2$ transitions. Moreover, only a slight increase in mean energy is required for a significant number of electrons to have sufficient energy to excite the $J = 1 \rightarrow 3$ transition, a transition that is possible for a further 30% of the molecules. As a result the mean electron energy rises only slowly initially. In the case of hydrogen, not only does the first rotational transition have its threshold at the higher value of 0.045 eV, but only 25% of the hydrogen molecules occupy the $J = 0$ level. The energy of the swarm therefore rises more rapidly until a considerable proportion of the electrons have an energy in excess of 0.075 eV, corresponding to the threshold of the $J = 1 \rightarrow 3$ transition. At higher energies the rise is less rapid and, in fact, above $E/N \sim 4 \times 10^{-18}$ V cm² it can be seen that the values of D/μ in hydrogen are less than the corresponding values in deuterium. This results from the fact that electrons lose twice as much energy in exciting a transition in hydrogen as they do in exciting the same transition in deuterium, so that, when rotational transitions play a significant role in determining the energy distributions in both gases, the power loss from these collisions may be greater in hydrogen than in deuterium.

At still higher energies significant numbers of electrons have enough energy to cause vibrational excitation of the molecules, the thresholds for this process being 0.516 and 0.360 eV in hydrogen and deuterium respectively (Herzberg 1950). The vibrational excitation process absorbs the additional energy supplied as the value of

E/N is increased and therefore causes a decrease in the slope of the D/μ against E/N curve. A similar explanation can be applied to the drift velocity curves shown in Figure 6.

Although this simple qualitative interpretation is possible, best use can be made of the data only by applying an analysis of the type described by Phelps and co-workers (e.g. Frost and Phelps 1962; Engelhardt and Phelps 1963) from which the energy dependence of the cross sections can be found. Such an analysis of the present data and of the data obtained in pure para-hydrogen (Crompton and McIntosh 1967) is being carried out.

V. ACKNOWLEDGMENTS

The authors wish to thank Mr. J. Gascoigne for invaluable technical assistance throughout the whole of this project and Mr. K. W. Goggin for perfecting the technique for making the shutters in the drift tube. One of us (A. I. McL.) wishes to acknowledge gratefully the financial assistance of an A.N.U. research scholarship during the tenure of which this work was carried out.

VI. REFERENCES

- CHANIN, L. M., PHELPS, A. V., and BIONDI, M. A. (1962).—*Phys. Rev.* **128**, 219.
 COCHRAN, L. W., and FORRESTER, D. W. (1962).—*Phys. Rev.* **126**, 1785.
 CROMPTON, R. W., and ELFORD, M. T. (1957).—*J. scient. Instrum.* **34**, 405.
 CROMPTON, R. W., and ELFORD, M. T. (1962).—*J. scient. Instrum.* **39**, 480.
 CROMPTON, R. W., and ELFORD, M. T. (1963).—Proc. 6th Int. Conf. on Ionization Phenomena in Gases, Paris, 1963. Vol. 1, p. 337.
 CROMPTON, R. W., ELFORD, M. T., and GASCOIGNE, J. (1965).—*Aust. J. Phys.* **18**, 409.
 CROMPTON, R. W., ELFORD, M. T., and JORY, R. L. (1967).—*Aust. J. Phys.* **20**, 369.
 CROMPTON, R. W., and JORY, R. L. (1962).—*Aust. J. Phys.* **15**, 451.
 CROMPTON, R. W., and MCINTOSH, A. I. (1967).—*Phys. Rev. Lett.* **18**, 527.
 CROMPTON, R. W., and SUTTON, D. J. (1952).—*Proc. R. Soc. A* **215**, 467.
 ELFORD, M. T. (1966).—*Aust. J. Phys.* **19**, 629.
 ENGELHARDT, A. G., and PHELPS, A. V. (1963).—*Phys. Rev.* **131**, 2116.
 FARKAS, A. A. (1935).—“Ortho-hydrogen, Para-hydrogen and Heavy Hydrogen.” (Cambridge Univ. Press.)
 FROST, L. S., and PHELPS, A. V. (1962).—*Phys. Rev.* **127**, 1621.
 GERJUOY, E., and STEIN, S. (1955).—*Phys. Rev.* **98**, 1848.
 HERZBERG, G. (1950).—“Spectra of Diatomic Molecules.” (D. Van Nostrand: Princeton.)
 HURST, C. A., and LILEY, B. S. (1965).—*Aust. J. Phys.* **18**, 521.
 HUXLEY, L. G. H., and CROMPTON, R. W. (1955).—*Proc. phys. Soc. B* **68**, 381.
 HUXLEY, L. G. H., and CROMPTON, R. W. (1962).—In “Atomic and Molecular Processes”. (Ed. D. R. Bates.) p. 335. (Academic Press: New York.)
 LILEY, B. S. (1967).—*Aust. J. Phys.* **20**, 527.
 LOWKE, J. J. (1962).—*Aust. J. Phys.* **15**, 39.
 LOWKE, J. J. (1963).—*Aust. J. Phys.* **16**, 115.
 MCINTOSH, A. I. (1966).—*Aust. J. Phys.* **19**, 805.
 NIELSEN, R. A. (1936).—*Phys. Rev.* **50**, 950.
 PACK, J. L., VOSHALL, R. E., and PHELPS, A. V. (1962).—*Phys. Rev.* **127**, 2084.
 PURSAR, K. H., and RICHARDS, J. R. (1959).—*J. scient. Instrum.* **36**, 142.
 TOWNSEND, J. S., and BAILEY, V. A. (1921).—*Phil. Mag.* **42**, 873.
 WARREN, R. W., and PARKER, J. H. (1962).—*Phys. Rev.* **128**, 2661.
 YOUNG, J. R. (1963).—*Rev. scient. Instrum.* **34**, 891.

