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The Drift Velocity of Electrons in Carbon Dioxide at Temperatures between 193 and 573 K

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Abstract

The drift velocity of electrons in carbon dioxide has been measured at gas temperatures ranging from 193 to 573 K and at E/N values up to 20 Td at 193 K, 50 Td at 293 K and 40 Td at 573 K. The measured drift velocities were found to decrease linearly with increasing gas number density at a given value of E/N for gas temperatures less than 293 K. This dependence has been attributed to multiple scattering and the data have been extrapolated to zero number density to correct for this effect. Comparisons are made with previous measurements where available. The present data for the variation of μN(thermal) with temperature agree to within the experimental error with the data of Pack *et al.* (1962).

1. Introduction

A knowledge of the cross sections for the scattering of electrons from CO_2 molecules is necessary in order to model the behaviour of CO_2 gas lasers, and consequently these cross sections have attracted considerable interest. Information concerning the cross sections has been obtained at relatively high electron energies by beam methods but at low energies the information has been derived from analyses of electron transport coefficients. The inclusion of information from beam studies is necessary in these transport coefficient analyses in order to reduce the lack of uniqueness in the cross sections.

There have been three analyses of electron transport coefficients in CO_2 to obtain cross sections: those of Hake and Phelps (1967), Lowke *et al.* (1973) and Bulos and Phelps (1976). Since no new drift and diffusion data were published in the period 1967–76 each of these analyses used the same data for the drift velocity v_{dr} and the ratio $D_{\perp}/\mu$ (where $D_{\perp}$ is the transverse diffusion coefficient and μ the electron mobility defined as v_{dr}/E, with E the electric field strength). Lowke *et al.* included information on vibrational excitation obtained by Andrick *et al.* (1969) and Stomatovic and Schultz (1969), while the analysis of Bulos and Phelps had the additional constraint provided by their own measurements of the rate coefficient for the excitation of the asymmetric stretch mode from spectroscopic studies of electron swarms in a drift tube.

The analysis of transport coefficients for CO_2 would be improved if more accurate data were available over a wider range of E/N values (where N is the gas number density). One particular deficiency, which was pointed out by Hake and Phelps (1967), is the absence of accurate drift velocity information in the E/N range 21–150 Td (1 Td $\equiv 10^{-21}\,\mathrm{V\,m^2}$).

The drift velocity data used in all the analyses for the lower E/N range have been those of Elford (1966) for 293 K. These data were obtained using the Bradbury–Nielsen time of flight method and were restricted to E/N values below about 20 Td due to the inability of the amplifiers used at that time to provide sufficiently large undistorted sinusoidal signals to the electrical shutter grids. With the availability of amplifiers with much larger output voltages this restriction no longer applied and it was therefore possible to extend the data to higher values of E/N.

Drift velocity measurements are subject to two effects which are functions of the gas number density N. The first, due to diffusion, causes the measured transit time t_m to be related to the number density by

$$t_m = t_0(1 + C'/N),$$

where C' is a constant for a given E/N value. The second effect causes a linear increase of the measured transit times with increasing number density. An explanation of this second effect at very high number densities was provided by Legler (1970) but it did not account satisfactorily for the dependence at low number densities such as was found in the studies by Crompton and Robertson (1971). Recently Braglia and Dallacasa (1978) and O'Malley (1980) have proposed theories to explain the effect at low densities. In order to study and correct for both these dependences on the gas number density it is necessary to take data over a wide range of number densities at each value of E/N.

An examination of the drift velocity data of Elford (1966) shows that there is no dependence of the drift velocity on N to within the experimental scatter ($\pm 0 \cdot 1\,\%$) over the range of number densities used in these measurements. However, O'Malley has predicted that the density dependence due to quantum mechanical effects increases as the mean electron energy decreases, and thus it seemed possible that a linear dependence on N might be observed at low E/N values and at temperatures below 293 K. Measurements have therefore been made at 193 K and over a wider range of values of N than was used by Elford in order to investigate this possibility. There is an additional reason for taking data over a wide range of gas temperatures. If such data at a given temperature are extrapolated to $E/N = 0$ one obtains the value of μN for an electron swarm in thermal equilibrium with the gas molecules. Values of μN_{th} (as the thermal value will be denoted) as a function of the gas temperature T can be analysed to obtain the momentum transfer cross section σ_m without having to carry out a numerical solution of the Boltzmann equation, the electron energy distribution being a known Maxwellian. The procedure of fitting to the μN_{th} values to obtain σ_m was developed by Pack *et al.* (1962) and applied to their data which covered the temperature range 195–413 K. The technique suffers from the disadvantage, however, that the momentum transfer cross section can only be obtained over a limited range of electron energies.

The momentum transfer cross section derived from an analysis of electron transport data as a function of E/N can be checked by comparing the temperature dependence of μN_{th} values calculated from the cross section with those obtained directly from the experimental data. To perform such a comparison it is desirable to have available μN_{th} data over the largest possible temperature range. Drift velocity data have therefore been taken at 573 K giving a total temperature range of 193–573 K.

2. Experimental Techniques

The drift velocities were measured by the Bradbury–Nielsen time of flight method using two drift tubes. The first drift tube (A) has been described in detail by Elford (1972) and Huxley and Crompton (1974) and was used for measurements at 193 and 293 K. This drift tube is the same as that used by Elford (1966) in his earlier measurements of electron drift velocities in CO_2, with the modification that the electron source is now of the type described by Crompton and Elford (1973).

The second drift tube (B) was used for measurements at 293 and 573 K and has been described in detail by Elford (1980). The drift lengths at 293 K were 100·00 mm and 150·90 mm for drift tubes A and B respectively. All pressures in both drift tubes were measured by a quartz spiral gauge (Texas Instruments Ltd) calibrated against a dead-weight tester using the method described by Gascoigne (1972). The dead-weight tester was checked against the standards held by the Division of Applied Physics, CSIRO. The error in the pressure measurement was less than $\pm 0 \cdot 1\%$ for all pressures used. The method of operation of this type of drift tube to obtain high accuracy is discussed by Huxley and Crompton (1974) and will not be considered further here.

It should be noted that all data reported for CO_2 using drift tube B were taken with the pressure gauge connected directly to the drift tube. The null detector pressure measurement system used in the electron drift velocity measurements in mercury vapour described previously (Elford 1980) was not used in the present work.

(*a*) *Operation of drift tube A at low temperatures*

In order to operate drift tube A at low temperatures the glass envelope was immersed in an alcohol bath which was cooled by drawing cold nitrogen gas through a heat exchanger consisting of a number of turns of copper tubing fitted inside the Dewar containing the alcohol. The gas flow rate which determined the bath temperature was controlled by a needle valve between a rotary vacuum pump and the heat exchanger. The cold nitrogen was taken from above boiling liquid nitrogen. Nitrogen gas was bubbled through the alcohol from the bottom of the bath to provide some circulation of the coolant.

The temperature of the gas was taken to be that of the electrode structure which was measured by reference to the bath temperature. Two copper–constantan thermocouples, attached to electrodes which terminate the drift space, were used with their reference junctions in the alcohol bath. In this way the temperature differentials between the electrodes and the bath were measured as well as temperature gradients across the drift space. The temperature difference recorded by these thermocouples was typically 0·5 K but under very stable conditions the difference was less than 0·1 K. The bath temperature was measured by a platinum resistance thermometer and a Leeds & Northrup portable precision temperature bridge (Type 8078) with an uncertainty of less than 0·1 K. Checks made using an independent copper–constantan thermocouple showed that there was no significant vertical temperature gradient in the alcohol bath. The bath temperature was stable to $\pm 0 \cdot 5$ K over 24 h.

Over most of the pressure range, temperature equilibrium between the electrodes and the bath was quickly achieved after gas was admitted. However, at low pressures ($< 2 \cdot 7$ kPa) the attainment of temperature equilibrium required periods of the order of 10 h.

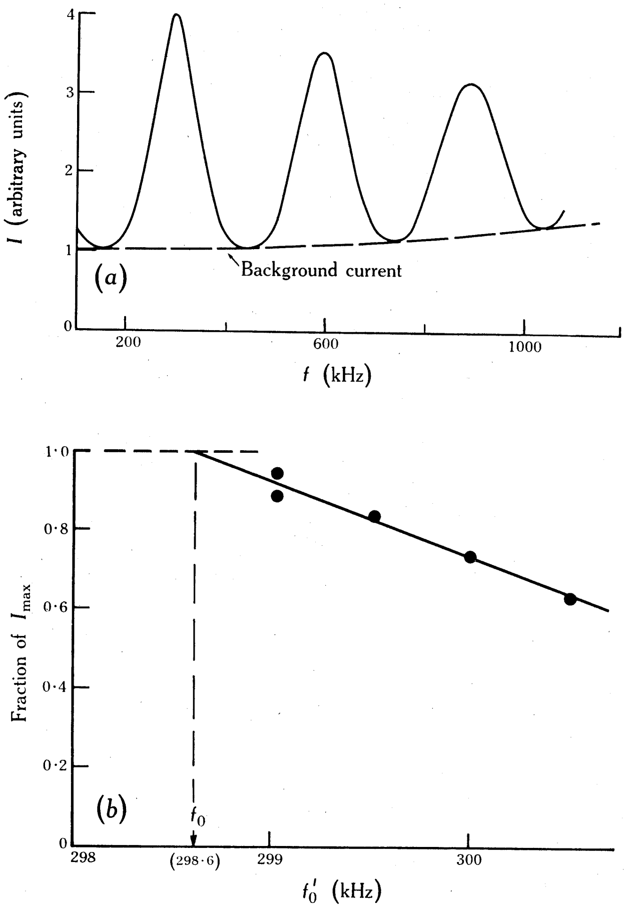

Fig. 1. Typical example for electrons in CO_2 at 30 Td and 0·331 kPa of:
(*a*) the arrival time spectrum, for the transmitted current I versus the shutter frequency f, showing the background current which is due to inefficient operation of the shutter grids at high E/N values and which causes the peaks in the spectrum to be skewed; no experimental points are shown as they all fall within the thickness of the curve;
(*b*) the frequency f_0' obtained by taking the mean of the two frequencies at which the current was a given fraction of the maximum current I_{max}; the frequency f_0 corresponding to I_{max} is found by extrapolation (298·6 kHz in this case).

(*b*) *Operation of drift tube B at high temperatures*

Details of the construction and temperature control of drift tube B have been given by Elford (1980). The temperature difference across the length of the manifold was less than 0·3 K for all measurements in CO_2, the temperature used to calculate the gas number density being taken as the mean of the temperatures recorded by the two thermocouples. The wire used for these thermocouples has been examined by the Division of Applied Physics, CSIRO, and the absolute error in temperature measurement is estimated to be less than 1·2 K or 0·2% at 573 K.

The tube was extensively outgassed before the CO_2 measurements (see Elford (1980) for details of the outgassing) to reduce the influx of H_2 and CO at 573 K. The outgassing was shown to have been reduced to an acceptable level by taking drift velocity data in CO_2 over periods of many hours. No changes to within the experimental scatter of $\pm 0 \cdot 2\%$ were observed.

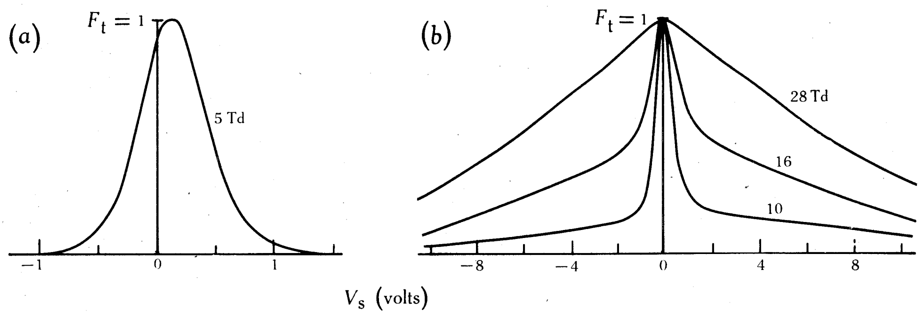

Fig. 2. Fraction F_t of the incident current transmitted by a shutter as a function of the potential difference V_s between adjacent wires of the shutter, under the conditions: (*a*) $0 \cdot 72$ kPa with $E/N = 5$ Td and (*b*) $0 \cdot 33$ kPa with $E/N = 10$, 16 and 28 Td.

(*c*) *Experimental details*

The CO_2 used in both drift tubes was Matheson research grade and no further purification was carried out.

At E/N values greater than about 10 Td at 293 K the maxima in the arrival time spectrum were found to be skewed due to a background current which increased linearly with increasing shutter signal frequency. A typical arrival time spectrum taken using drift tube B is shown in Fig. 1*a* for $E/N = 30$ Td and a pressure $p = 0 \cdot 331$ kPa. The frequency f_0 at which the maximum current occurs is not changed by this background current. However, the normal method of determining f_0 by measuring the two frequencies at which the current is reduced to say 70% of the maximum value and then taking f_0 to be the mean of these two values would result in error. Therefore, a series of measurements were made of the two frequencies at which the current was say 30%, 40%, 50%, 60% etc. of the maximum value. The mean value of each pair was determined, and a plot of the mean value versus the transmitted current was then extrapolated to give the required value of f_0, as shown in Fig. 1*b*.

From the example in Fig. 1 it can be seen that if the effect of the skewed peak had been ignored it would have introduced an error of the order of $0 \cdot 5\%$ into the value of f_0 and hence v_{dr}. The scatter of the two data points at the current close to the maximum value (see Fig. 1*b*) is due to the slow change of current with frequency in this frequency range, making measurements more subject to error. The peaks were found to be more skewed as the pressure decreased and/or E/N increased. This was caused by a larger background current due to a decreasing attenuation efficiency of the shutters as p decreased and E/N increased.

Fig. 2 shows plots of the transmitted current as a function of V_s, the voltage between adjacent wires of the shutter grid. The curve in Fig. 2*a* is for $E/N = 5$ Td and $p = 0 \cdot 7231$ kPa and is typical of these found at low E/N values and high pressures. This may be contrasted with the curves in Fig. 2*b* which were taken at $p = 0 \cdot 3306$ kPa and at E/N values from 10 to 28 Td. Thus, as E/N increases, very large values of V_s would be required to attenuate adequately the current transmitted by each shutter. When making drift velocity measurements, such large values of V_s can only be attained by applying large amplitude sinusoidal signals to the shutter grids, the maximum amplitude being limited by the onset of distortion by the shutter signal amplifier. The second factor which limits the signal amplitude that can be used is the rapid decrease in open time of the shutters, and hence transmitted current,

Table 1. Drift velocity of electrons in CO_2 between 193 and 573 K

All entries for the drift velocity v_{dr} in (*a*), (*b*) and (*c*) have been corrected for deviations from an ideal gas (IG correction as shown for (*a*)); the correction is negligible at 293 and 573 K. All μN values are in units of $10^{22}\,cm^{-1}\,s^{-1}\,V^{-1}$

(*a*) *T* = *193 K*

E/N	v_{dr} ($10^5\,cm\,s^{-1}$) at N ($10^{17}\,cm^{-3}$) of:								$v_{dr(0)}$	$\mu N_{(0)}$
(Td)	2·72	5·04	10·1	24·8	50·4	77·6	101	132	($10^5\,cm\,s^{-1}$)	
0·1					0·1810	0·1795	0·1792	0·1781	0·1826	1·826
0·14					0·2533	0·2515	0·2509	0·2494	0·2555	1·825
0·17					0·3072	0·3054	0·3044	0·3026	0·3099	1·823
0·2					0·3612	0·3592	0·3580	0·3560	0·3644	1·822
0·25					0·4511	0·4485	0·4472	0·4447	0·4550	1·820
0·3					0·5406	0·5379	0·5360	0·5333	0·5451	1·817
0·35					0·6300	0·6271	0·6250	0·6217	0·6346	1·813
0·4				0·7207	0·7194	0·7162	0·7138	0·7101	0·7248	1·812
0·5				0·8994	0·8973	0·8940	0·8909	0·8868	0·9040	1·808
0·6			1·080	1·078	1·076	1·072	1·068	1·064	1·082	1·803
0·7			1·258	1·255	1·253	1·250	1·245	1·240	1·261	1·801
0·8			1·437	1·433	1·431	1·427	1·422		1·438	1·798
1·0		1·794	1·793	1·788	1·786	1·781			1·795	1·795
1·2		2·149	2·148	2·143	2·141	2·135			2·150	1·792
1·4		2·503	2·503	2·496	2·494				2·505	1·789
1·7		3·035	3·034	3·027	3·025				3·036	1·786
2·0		3·568	3·567	3·559					3·572	1·786
2·5		4·463	4·458	4·446					4·465	1·786
3·0		5·364	5·354	5·344					5·364	1·788
3·5		6·276	6·263	6·251					6·276	1·793
4·0		7·202	7·188	7·172					7·204	1·801
5·0	9·122	9·105	9·088						9·120	1·824
6·0	11·12	11·11	11·09						11·13	1·855
7·0	13·21	13·23	13·20						13·24	1·892
8·0	15·52	15·50	15·48						15·57	1·946
10·0	20·72	20·71	20·69						20·74	2·074
12·0	27·18	27·15							27·22	2·268
14·0	35·23	35·17							35·28	2·520
17·0	49·71	49·63							49·81	2·930
20·0	64·14	64·10							64·20	3·210
IG correction (%):			0·07	0·16	0·34	0·52	0·67	0·88		

(*b*) *T* = *224 K*

E/N	v_{dr} ($10^5\,cm\,s^{-1}$) at N ($10^{17}\,cm^{-3}$) of:		
(Td)	43·4	86·9	114
0·4	0·7176	0·7127	0·7099
0·5	0·8951	0·8896	0·8862
0·6	1·073	1·068	1·063
0·7	1·250	1·243	1·239
0·8	1·428	1·420	1·415
1·0	1·783	1·773	
1·2	2·138		
1·4	2·491		
1·7	3·022		

(*c*) *T* = *256 K*

E/N	v_{dr} ($10^5\,cm\,s^{-1}$) at N ($10^{17}\,cm^{-3}$) of:		
(Td)	38·0	76·0	99·4
0·4	0·7142	0·7125	0·7105
0·5	0·8915	0·8879	0·8865
0·6	1·068	1·065	1·063
0·7	1·245	1·242	1·240
0·8	1·424	1·420	1·417
1·0	1·777	1·773	
1·2	2·131		
1·4	2·485		
1·7	3·014		

Table 1 (*Continued*)

(*d*) $T = 293$ K

E/N (Td)	v_{dr} (10^5 cm s^{-1}) at N (10^{17} cm^{-3}) of: 0·510	0·817	1·018	1·781	3·308	6·617	13·23	25·42	Best v_{dr} estimate	μN
0·4								0·712	0·712	1·780
0·5								0·890	0·890	1·780
0·6								1·067	1·067	1·778
0·7								1·245	1·245	1·779
0·8							1·424	1·422	1·423	1·779
1·0							1·779	1·778	1·779	1·779
1·2							2·134	2·132	2·133	1·778
1·4						2·493	2·488	2·486	2·489	1·778
1·7						3·028	3·023		3·025	1·779
2·0						3·560	3·558		3·559	1·780
2·5						4·455	4·450		4·453	1·781
3·0					5·361	5·355	5·352		5·355	1·785
4·0				7·200	7·200	7·192			7·196	1·799
5·0				9·100	9·100	9·090			9·095	1·819
6·0				11·08	11·08	11·08			11·08	1·847
7·0				13·18	13·19				13·19	1·884
8·0			15·46	15·42	15·43				15·43	1·929
10·0		20·50	20·50	20·48	20·49				20·49	2·049
12·0		26·70	26·70	26·65					26·69	2·224
14·0		34·41	34·47	34·36					34·43	2·459
16·0		43·49	43·60						43·55	2·722
18·0		53·30	53·33						53·32	2·962
20·0	62·56	62·58	62·58						62·58	3·129
22·0	70·71	70·75	70·69						70·71	3·214
24·0	77·38	77·50							77·42	3·226
26·0	82·63	82·78							82·68	3·180
28·0	86·91	86·97							86·94	3·105
30·0	89·94	90·12							90·03	3·001
35·0	96·67								96·67	2·762
40·0	101·1								101·1	2·528
45·0	106·6								106·6	2·342
50·0	110·2								110·2	2·203

(*e*) $T = 573$ K

E/N (Td)	v_{dr} (10^5 cm s^{-1}) at N (10^{17} cm^{-3}) of: 0·522	0·914	1·696	2·395	6·796	25·42	Best v_{dr} estimate	μN
1·0						1·744	1·744	1·744
1·2						2·093	2·093	1·744
1·4					2·447	2·441	2·444	1·746
1·7					2·973	2·964	2·969	1·746
2·0				3·508	3·500	3·494	3·500	1·750
2·5				4·387	4·382		4·385	1·754
3·0				5·280	5·267		5·274	1·758
3·5				6·170	6·163		6·167	1·762
4·0			7·088	7·076	7·068		7·077	1·769
5·0			8·931	8·915			8·923	1·784
6·0			10·83	10·81			10·82	1·803
7·0			12·79	12·77			12·78	1·826
8·0		14·86	14·84				14·85	1·857
10·0		19·37	19·32				19·35	1·935
12·0	24·61	24·54	24·51				24·51	2·043
14·0	30·84	30·78	30·64				30·64	2·189
16·0	37·69	37·88					37·88	2·368
18·0	45·82	46·03					46·03	2·557
20·0	53·96	54·22					54·22	2·711
22·0	62·00	62·24					62·24	2·829
24·0		69·24					69·24	2·885
26·0		75·15					75·15	2·890
32·0	88·19						88·19	2·756
40·0	97·73						97·73	2·443

as the signal amplitude increases. It was the first factor which limited the E/N range in the measurements of Elford (1966) but the second factor determined the upper E/N limit in the present measurements. Although the problem of low transmitted current at high E/N values can be avoided by gating the shutters by square wave pulses, there are electronic difficulties in obtaining large amplitude undistorted voltage pulses at the shutters, particularly at high pulse rates.

If the skewness in the arrival time spectra is not taken into account the values of f_0 and hence v_{dr} and μN will be too high. Since the skewness decreases with increasing pressure, measurements made over a range of pressures at a given E/N value will have an apparent pressure dependence, the measured drift velocity decreasing as the pressure increases.

(*d*) *Checks on experimental accuracy*

The accuracy of both drift tubes A and B was checked by taking data for cases where the drift velocity is considered to be known with high accuracy. In the case of drift tube A, a measurement was made in hydrogen at 293 K at $E/N = 0{\cdot}3641$ Td and $p = 26{\cdot}9$ kPa. The value obtained for the drift velocity was $3{\cdot}547\times10^5$ cm s^{-1} which is in excellent agreement with the value obtained by Elford (1969) of $3{\cdot}546\times10^5$ cm s^{-1}. No other checks on the experimental accuracy were made at lower temperatures.

In the case of drift tube B, a measurement of the drift velocity was made in helium at 553 K, $E/N = 0{\cdot}3$ Td and pressures of $10{\cdot}33$ and $14{\cdot}46$ kPa. After correction for diffusion effects the drift velocity was found to be $2{\cdot}50\times10^5$ cm s^{-1}. There are no experimental values of electron drift velocities at 553 K with which this value can be compared but the drift velocity can be calculated with an uncertainty of less than 1% from the momentum transfer cross section of Crompton *et al.* (1970) and Milloy and Crompton (1977). The calculated value is $2{\cdot}52\times10^5$ cm s^{-1}, the difference between the experimental and calculated values being less than 1%. It should be noted that in the measurement using helium gas the null detector pressure measurement system was used and this may introduce a small additional error. However, the agreement stated above is within the uncertainty of the calculated value and it can be concluded that there is no systematic error greater than ±1% in the measurements taken at this temperature.

Additional checks on the accuracy of the drift tubes were made by comparing data taken in CO_2 at 293 K with the earlier data of Elford (1966). The data and comparisons are given in Section 3.

3. Experimental Results

At low temperatures, drift velocity data were corrected to account for the departure from perfect gas behaviour using virial coefficient data taken from Dymond and Smith (1969). The drift velocity of electrons in CO_2 at 193, 224, 256, 293 and 573 K are shown in Table 1, as a function of the number density. The correction applied to the drift velocity to account for deviations from perfect gas behaviour is shown at the end of the Table 1*a*. For data at 293 K and above (Tables 1*d* and 1*e*), the correction is negligible over the range of number densities used in this work. The changes in drift length due to changes in temperature have been taken into account in these data. In drift tube A the drift length decreased from $100{\cdot}00$ to $99{\cdot}91$ mm over the temperature range 293–193 K while in drift tube B the drift length increased from 150·9 to 151·3 mm over the temperature range 293–573 K.

The values of μN corresponding to the best estimate values, which are also shown in Tables 1*a*, 1*d* and 1*e*, are plotted in Fig. 3.

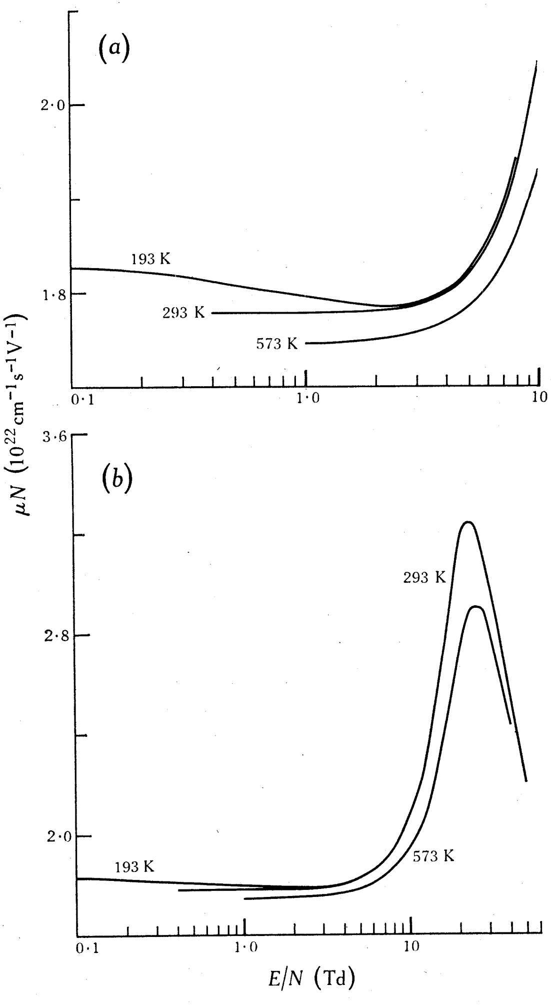

Fig. 3. Experimental values of μN as a function of E/N for electrons in CO_2 at temperatures of 193, 293 and 573 K, for (*a*) $0 \cdot 1 \leqslant E/N \leqslant 10$ and (*b*) over the full experimental range. The scales in (*a*) have been chosen to demonstrate the behaviour of μN at low values of E/N. No data points are shown as they all fall within the thicknesses of the curves.

At temperatures below 293 K the measured drift velocity decreases linearly with increasing number density. Typical variations are shown in Fig. 4*a* for data at 193 K. For a given E/N, the actual dependence on N of the measured drift velocity varies with the temperature. Typical variations are shown in Fig. 4*b* (for $E/N =$ 0·5 Td). The cause of these linear dependences is discussed in Section 4 where it is suggested that the drift velocity for use in analyses to obtain cross sections should be that corresponding to $N = 0$. Accordingly for each E/N value the data have been extrapolated to $N = 0$ to obtain $v_{dr(0)}$. Values of μN denoted $\mu N_{(0)}$ which correspond to $v_{dr(0)}$ are shown in Table 1*a*. It is these values of μN which are plotted in Figs 3*a* and 3*b* for 193 K.

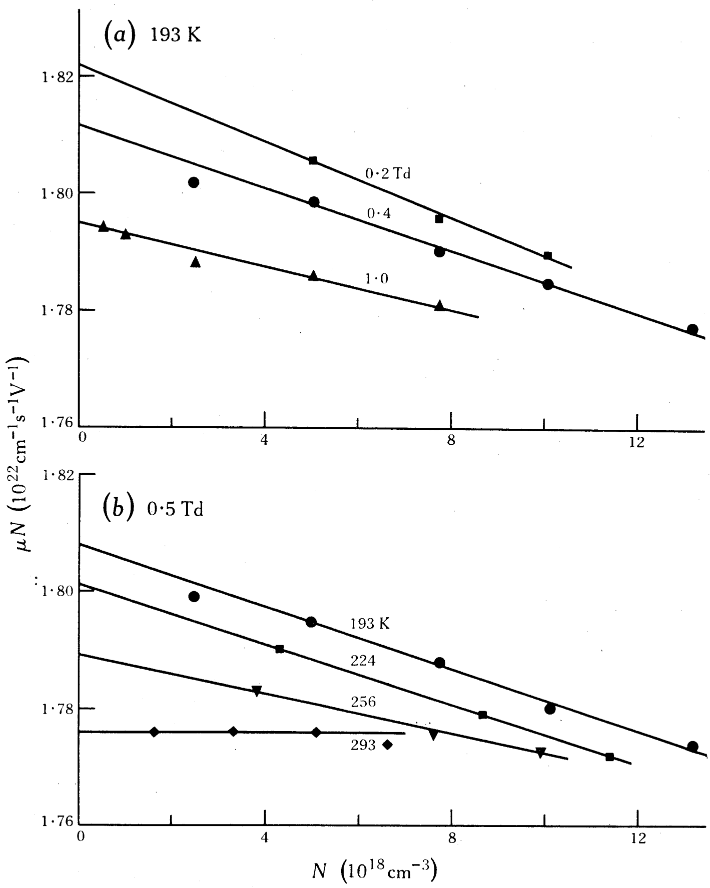

Fig. 4. Experimental values of μN as a function of the CO_2 number density N for (*a*) a temperature of 193 K and E/N values of 0·2, 0·4 and 1·0 Td and (*b*) $E/N = 0{\cdot}5$ Td at 193, 224, 256 and 293 K.

There is an additional dependence on number density due to diffusion effects. These effects cause the measured drift velocity to decrease with increasing N and should be evidenced in the plots of v_{dr} versus N at a given E/N value as a departure from the linear relation at low N values. The drift velocity is determined from the transit time measurement by using a formula of the form (Huxley and Crompton 1974)

$$v'_{dr} = h\{t_m(1-C\beta)\}^{-1},$$

where v'_{dr} is the drift velocity in the absence of diffusion effects, t_m is the measured transit time, h is the drift length, C is a factor of order 3 and $\beta = (D_{\|}/\mu)/Eh = (D_{\|}/\mu)/(E/N)hN$, with $D_{\|}$ the longitudinal diffusion coefficient. Calculations of β for the present measurements give a maximum value of 0·0009, indicating that with $C = 3$ the worst error in using the approximation $v_{dr} = h/t_m$ is of the order of 0·2%.

This is confirmed by the fact that no significant departure was observed from the linear relationship between v_{dr} and N discussed above. Thus in these measurements diffusion effects may be ignored.

The estimated error in the $v_{dr(0)}$ values for 193 K, shown in Table 1*a*, is $\pm 1\%$ over the whole E/N range. The estimated error in the best estimate values of v_{dr} shown in Table 1*d* for 293 K is $\pm 0 \cdot 5\%$ for $E/N < 10$ Td, $\pm 1\%$ for $10 \leqslant E/N \leqslant 30$ Td and $\pm 2\%$ for $E/N > 30$ Td. The estimated error in the best estimate values of v_{dr} shown in Table 1*e* for 573 K is $\pm 0 \cdot 5\%$ for $E/N < 10$ Td; $+1 \cdot 5, -1 \cdot 0\%$ for $10 \leqslant E/N \leqslant 20$ Td; and $+3, -2\%$ for $E/N > 20$ Td.

4. Discussion

(*a*) *Comparison with previous data for* μN *as a function of* E/N

(*1*) *293 K*

Three sets of data for 293 K have been taken using drift tubes A and B. The first set was that of Elford (1966) using drift tube A while the other two sets of data were taken during the present work using both drift tubes. A comparison establishes the degree of consistency in the measurements.

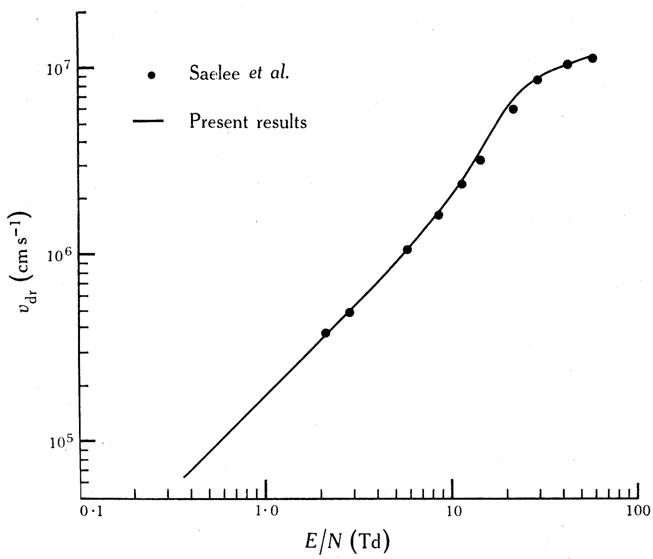

Fig. 5. Comparison of the present results for the electron drift velocity v_{dr} as a function of E/N with those of Saelee *et al.* (1977). No data points for the present work are shown as they all fall within the thickness of the curve.

Over the common range of E/N values, the best estimate values of the drift velocity obtained using tube B agree with the best estimate values of Elford (1966) to within $0 \cdot 3\%$ at all E/N values and to within $0 \cdot 2\%$ for $E/N < 5$ Td. The error limits claimed by Elford (1966) were $0 \cdot 5\%$ for $0 \cdot 3 \leqslant E/N \leqslant 9 \cdot 1$ Td and 1% for $9 \cdot 1 < E/N < 21$ Td. The agreement is therefore inside the claimed error limits. The data taken at 293 K using drift tube A covered the E/N range $0 \cdot 5$–$2 \cdot 0$ Td and were systematically $0 \cdot 3\%$ lower than the best estimate values of Elford (1966). This difference also lies inside the stated error limits.

Fig. 5 shows the present data as a function of E/N together with the most recently published comparable data, namely those of Saelee *et al.* (1977) taken with a Bradbury–Nielsen system. At E/N values less than 12 Td their values are up to 2·5% lower than the present data. The difference increases, however, at higher E/N values and is 12% at $E/N = 21$ Td. Saelee *et al.* also measured electron drift velocities with a second apparatus by analysing current transients. The drift velocity values at 28 and 57 Td obtained with this apparatus are about 2% higher than those obtained with their Bradbury–Nielsen system.

There have been a number of other previous measurements of electron drift velocities in CO_2 at about 293 K, namely those by Riemann (1944), Errett (1951), Bortner *et al.* (1957), Frommhold (1960), Pack *et al.* (1962), Levine and Uman (1964), Schlumbohm (1965) and Elford (1966). The data of Pack *et al.* and of Bortner *et al.* have already been discussed by Elford (1966) while the data of Schlumbohm, Frommhold and Riemann were taken at E/N values which were all higher than those used in the present work. The data of Levine and Uman cover a limited E/N range 1–6 Td and have a high uncertainty (±5%).

(*2*) *193 K*

Only Pack *et al.* (1962) have published data at a low temperature in CO_2. Their results for μN at 195 K cover the very low E/N range 0·006–0·3 Td and are independent of E/N to within the scatter of the data points, approximately ±2%. Only one pressure was used in these measurements and hence no pressure dependence, such as found in the present work, could have been observed. The data of Pack *et al.* agree with the present values over the common E/N range to within the experimental uncertainty.

(*3*) *224, 256 and 573 K*

There are no data available with which the present data for 224, 256 and 573 K can be compared.

(*b*) *Comparison of* μN_{th} *values as a function of T*

As mentioned in the Introduction there are some specific advantages in using μN_{th} data in analyses to determine the momentum transfer cross section. The present data were therefore taken at sufficiently low values of E/N that the electron swarm was close to thermal equilibrium with the gas molecules. The values of μN were then virtually independent of further decrease in the E/N value, making the extrapolation to zero E/N an accurate procedure. The values of μN_{th} obtained in the present work are compared in Fig. 6 with the values of Pack *et al.* (1962). The present μN_{th} values agree with those of Pack *et al.* over the entire common temperature range 195–413 K to within the combined error limits if an uncertainty of ±2% is placed on the μN_{th} values of these workers.

(*c*) *Comparison of observed density dependence of drift velocity with theoretical predictions*

Recently O'Malley (1980) has explained the anomalous density dependence of electron mobilities in terms of multiple scattering theory. In its simplest form, the theory predicts an approximately linear dependence of v_{dr} on N over the range of densities used in the present work. An increase of v_{dr} with N is correctly predicted but the magnitude of the effect is a factor of 2–3 too large when compared with the experimental results. According to O'Malley the theory has a tendency to overestimate these effects and it seems reasonable to assume that this is the correct explanation for the pressure effect observed in the present results.

In order to eliminate the effects of multiple scattering, all results showing a dependence on N have been extrapolated to zero number density.

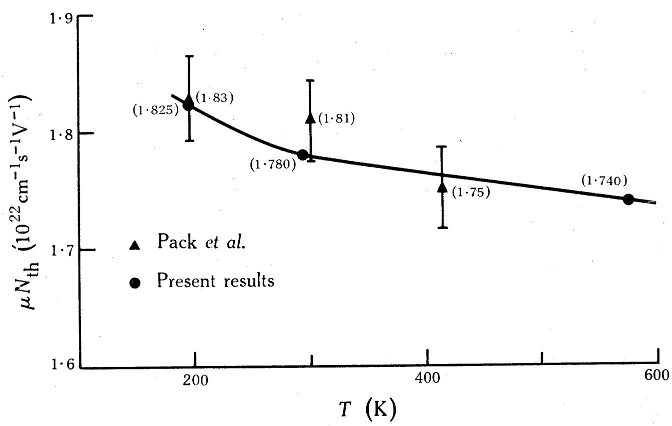

Fig. 6. Comparison of the present results for μN_{th} as a function of temperature with those of Pack *et al.* (1962). The present results (at 193, 293 and 573 K) were obtained by extrapolation to $E/N = 0$ and are estimated to be in error by less than 1%. The error bars shown on the values of Pack *et al.* (at 195, 300 and 413 K) are $\pm 2\%$ (see text).

5. Conclusions

The present data for the electron drift velocity in CO_2 at 293 K complement the data of Elford (1966) and now provide a complete set from $E/N = 0{\cdot}3$ to 50 Td with absolute errors which range from 0·5% to 2%. The extension of the range of E/N over which data of this accuracy are available should significantly reduce the uncertainty in the cross sections obtained by fitting these data using a solution of the Boltzmann equation. It should be noted, however, that the conventional two-term solution of the Boltzmann equation is not adequate for the case of CO_2 (Haddad and Elford 1979) and more sophisticated solutions (Lin *et al.* 1979; Pitchford and O'Neil 1979) will be required.

The present data confirm the μN_{th} variation with gas temperature obtained by Pack *et al.* (1962) and extend the temperature range to 573 K. The μN_{th} versus T variation serves as a rigorous check on derived momentum transfer cross sections. It should be noted that the value of μN_{th} at 573 K is inconsistent with the momentum transfer cross section derived using 293 K data (see Haddad and Elford 1979).

A linear decrease of the measured drift velocity with increasing gas number density at low temperatures and low values of E/N has been observed. The effect recorded in this work is much larger than any such effect found in previous measurements of the drift velocity in gases at relatively low number densities, but it has been shown to be in qualitative agreement with the predictions of a theory proposed by O'Malley (1980).

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