Electron Drift and Diffusion in Counting Gases

by

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H. Dip. Ed., B.Sc., M.Sc.

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<u>ERRATA</u>

<u>Page</u>	<u>Paragraph</u>	<u>Line</u>	Should read	
26	2	2	- after inelastic encounter	
32	1	2	$\underline{\mathbf{f}}_{1}(\mathbf{c}) = -\underline{\mathbf{e}}_{\overline{\mathbf{mv}}} \frac{\mathbf{d}}{\mathbf{dc}} \mathbf{f}_{0} = -\mathbf{V}' \frac{\mathbf{d}}{\mathbf{dc}} \mathbf{f}_{0} \qquad [2.19]$	
32	1	8	$v = v_{e1} + \sum_{\mathbf{k}} \left[v_{ok_{in}} I(c - c_{k_{in}}) + v_{ok_{in}} \right] [2.19']$	
33	equation	[2.24]	$\int_{0}^{\infty} \varepsilon^{\frac{1}{2}} f_{0}(\varepsilon) d\varepsilon = 4 \Pi \int_{0}^{\infty} c f_{0}(c) dc = 1 [2.24]$	
37		10	$\frac{\partial n}{\partial t} = \operatorname{div}_{\mathbf{r}} \left[\operatorname{grad}_{\mathbf{r}} \left(\frac{4 \operatorname{II} n}{3} \int_{\mathcal{V}}^{\mathcal{O}} \frac{c^2}{\nu} f_0 c^2 dc \right) \right]$	
			$-\operatorname{div}_{\mathbf{r}}\left[\frac{4\Pi}{3}\int_{0}^{\infty}\frac{e\underline{E}c}{m\nu}\frac{\partial}{\partial c}\left(nf_{0}\right)c^{2}dc\right]=0$	
38	1	9	- 3.3.2	
51	1	5	- the Townsend method and the T.O.F. method for measuring the lateral and longitudinal diffusion coefficients.	n
65	3	1	- 3.4 Transport Coefficient Studies of Previous Investigators:	
77	1	1	- berillium-copper from which the annuli	
81	1	1	circulation. The proportional counter	
94	5	2	type 532/D, 3.0 KV	
108	1	14	recorded in channel c_i and N is	
117	1	2	- The total spread σ_{τ}	
157	2	6	availability of cross-section data.	
160	2	1	from figure 7.1(a)	
161	2	6	, as shown in figure 7.2(b).	
164	3	9	, as figure 7.1(b) shows,	
172	2	2	lapping distributions is worth	

<u>ABSTRACT</u>

An experimental system has been designed with a twofold objective. The system, which has a variable drift length, has been used to measure, for a range of counting gases, drift velocities and longitudinal diffusion coefficients employing the time-of-flight method, and lateral diffusion coefficients using the Townsend method. Several problems have been encountered during the work, these requiring continued modification to be carried out on the system. A detailed description is given of the system and its stages of development.

Attempts to measure longitudinal diffusion coefficients were not successful and possible reasons are fully discussed.

A modified Boltzmann-Holstein equation has been employed with published cross-section data to calculate numerically the electron energy distribution, and hence electron transport coefficients, in the gas mixtures studied, at non-ionising field values. The Boltzmann-Holstein equation is discussed from first principles and the method of numerical solution is explained. Good agreement has been found between calculations and measurements of drift velocities for methane and a mixture of neon/10% methane and of D/μ for Ne/10% CH₄. Predictions for argon/methane and argon/carbon dioxide mixture are less accurate; possible reasons are discussed.

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CHAPTER 1

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HISTORIC REVIEW

1.1 Introduction

The measurement of the transport properties of electron swarms drifting and diffusing through gases began with the pioneering work of J. S. Townsend in the early years of this century. Townsend's work was initiated by the discovery of the electron and of X-rays about a decade before. As a new field of research then, the study of the transport properties in gases provided wide areas of investigations both theoretically and experimentally. The progress in the research activity, however, was relatively rather slow. This resulted in a decline in the field in the twenty years or so that followed Townsend's work. During that period the work was mainly concentrated in engineering applications. The decline in the research was due to two main reasons. Firstly, physicists seemed to be more enthusiastic in the, then rapidly advancing fields of atomic theory, radioactivity, X-rays and ionisation impact. The second reason was the increasing difficulty of further more accurate advance using the existing techniques.

Following the remarkable improvements in laboratory techniques and the great clarification of the atomic theory on the basis of quantum mechanics in the early thirties, the research activity in the field started to gather momentum again.

The introduction of time-of-flight methods that was made independently in 1928 by R. Van de Graaff and A. M. Tyndall and L. H. Starr and C. F. Powell for studying the ion mobilities, had considerably advanced the precision and reliability of measurement of this parameter. The

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time-of-flight methods, which incorporated electrical shutters operated at ratio frequencies, were successfully adapted by N. E. Bradbury and R. A. Nielson in 1936 for the measurement of drift velocities of electrons in gases as a function of E/p (the ratio of drift filed to gas pressure). [The basic concept of the Bradbury and Nielson method will be discussed in section 1.2.2.]

In 1940 L. G. Huxley simplified the theory of Townsend's apparatus for measuring drift velocity W, and the ratio of diffusion coefficient to drift velocity, D/W. These two quantities depended mainly upon the geometry of the diffusion chamber, i.e. the radius of the electron source hole, the drift length and the radius of the central anode disc, (half the width of the central strip in the case of the drift version of the apparatus). These three parameters are, respectively, designated a, h and b. The simplification introduced by Huxley was in making the radius, <u>a</u> much smaller than the other relevant dimensions. Huxley treated the 'hole source' as a point source and thus eliminating one of the parameters upon which the experimental values of W and D/Wdepended. Since 1950 workers in the field have, in general, taken advantage of the flexibility and accuracy implicit in this simpler theory in the design of their apparatus.

In recent years research activity in the field has increased considerably. Three main factors are responsible for the enhancement in research. Firstly, there has arisen a need for quantitative data for drift velocity and diffusion coefficients of electrons in gases and gas mixtures. Accurate knowledge of these quantities is important in many applications in several branches of science ranging from high energy physics and astrophysics to medical and biological science. Secondly, considerable success is now being achieved in analysing the transport

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properties to derive detailed information about elastic and inelastic collision cross-sections of electrons with gas molecules. Thirdly, there is a need for quantitative data for electron-loss processes such as attachment and recombination. Although these three factors are inter-related, perhaps the first factor is the most important in the area of gas filled detectors used in many applications nowadays, e.g. proportional counters associated with position sensitive and high energy drift chambers.

The importance of the second aspect can not be overlooked. Perhaps the most successful technique for evaluation of elastic and inelastic collision cross-sections from swarm data, is the iterative method introduced by Phelps and his colleagues in the early 1960's. In two fairly recent reviews Phelps (1967 and 1968), has covered many aspects of the application of swarm data in deriving detailed information about elastic and inelastic collision cross-sections. Phelps' method has, until the early 1970's, been applied to atoms and simple molecules only. However, Duncan and Walker (1972 and 1973) applied the method to more complicated molecules, mainly hydrocarbons. The knowledge of the various collision cross-sections becomes invaluable in showing the effects of impurities on the transport coefficients and in calculating these coefficients for gas mixtures.

1.1.1 Aim of the work

It is primarily the purpose of this work to study the transport coefficients of electrons travelling under the action of uniform electric fields in some of the gases which are potentially suitable in gas-filled detectors (e.g. proportional counters). A large number of pure gases and gas mixtures are known to give satisfactory operation

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in proportional counters. However, optimum operation is achieved by choosing the most suitable filling gas that satisfies the requirements of a particular application. To stress the importance of this, let us consider, as an example, the operation of drift chambers used in localisation of tracks of charged particles. High accuracy spatial and time resolutions, required in the operation of these detectors, depends, to a large extent, on the accurate knowledge of the transport parameters of electrons in the filling gas. The choice of gas is, therefore, determined by the diffusion broadening and the drift velocity. The inherent time and spatial resolutions of a drift-chamber are determined by the diffusion broadening (σ) in a uniform electric field (E) after drifting a distance (h) is given by:

$$\sigma^2 = 2 \int_0^n \frac{D(E)}{\mu(E)} \cdot \frac{dx}{E}$$

where D(E) is the diffusion coefficient, $\mu(E)$ is electron mobility and x is the direction of drift. Clearly a small D/μ ratio is desirable.

The other relevant parameter in the choice of gas is the drift velocity W and its dependence on the electric field E. A drift velocity saturated gas leads to linearity in the space-time relationship. This is certainly very useful in order to reduce the complexity of data analysis. A saturated operation makes the chamber response virtually independent of local imperfections that produce non-uniform fields and hence non-linear drift time. Further, in the saturation region the change of W with temperature, pressure and gas composition is minimal.

Experimental values of drift velocity W versus drift field E for many gases of interest may be found in the literature but these values

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show disturbingly large differences. The discrepancies in the drift velocity reported in the literature arise from the following reasons: (1) <u>Instrumental limitations</u>. These vary from one method to another and, therefore, depend upon the nature of the method and the design of the apparatus used in a particular experiment. However, there are two main limitations; (a) timing inaccuracies and (b) inaccuracies resulting from drift region geometry.

(2) <u>Gas contamination</u>. Perhaps one of the main factors causing the discrepancies in the drift velocity data reported in the literature, is the impurity of the gases. In many gases the drift velocity is extremely sensitive to impurities. For example, a few parts per million of O_2 can prevent accurate measurement of W in a large number of gases at low E/p values and at low temperature (Huxley and Crompton 1974). Furthermore, water vapour can seriously affect the accuracy of drift velocity experimental results in many gases, particularly at low E/p values. This is because water has relatively, very large low-energy elastic and inelastic collision cross-sections.

In the case of multi-component gases, in general, W depends upon the proportions in which the components are mixed. In many gases, very small inaccuracies in the proportions may result in considerable change in values of W.

(3) <u>Data analysis</u>. Discrepancies may arise from incorrect or incomplete data analysis. A number of processes may cause perturbations in the drift times of electrons, and in order to find the true drift time of a group of electrons travelling in a drift region, it is important to identify the perturbations and then make the necessary corrections in analysing the data. The processes in question are mainly diffusive, and their identification depends upon the kind of experiment being

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considered.

The considerations outlined above can, in general, have similar effects on the accuracy of the diffusion coefficient measurement. Experimental values for D as a function of E/p, available in the literature, are limited to fewer gases than those of W. Experimental data $\int_{a \in S_0}^{a \in S_0}$ of D, for multi-component/are particularly rare.

The major part of the work described in this thesis has been concerned with attempts to make accurate, reproducible measurements of electron transport coefficients in a range of counting gas mixtures. Appropriate new apparatus has been developed, initially in the light of previous work, and then modified or even re-designed as the investigations proceeded.

A second concern of the present work has been the numerical calculations of theoretical values for comparison purposes. Theoretical work on multi-component gases has been reported in the literature only rarely, mainly because of lack of cross-section data, and then using approximations of seriously limited value (the recent work of Schultz and Gresser 1978 is an exception).

1.2 Measurement of Electron Drift Velocity

The drift velocity of electrons in gases has been subject to a great deal of experimental investigations in which a large number of methods has been used. These methods, however, can be classified into three basic categories. Each covers a number of experiments which are essentially similar in principle but may vary in the details. These principle methods are: (1) the Townsend method, (2) the electrical shutter method, and (3) the pulse method. These three principle

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methods are responsible for the largest body of information on the drift velocity of electrons in gases travelling under the action of steady fields.

The basic concept of each of the three methods will now be outlined. Special emphasis, however, will be given to the type of method adopted in this work. For more complete account see Loeb (1955), Huxley and Crompton (1974).

1.2.1 The Townsend Method

The basic principle of this method was introduced by J. Townsend in the early 1900's. It has since been subject to constant development and improvement by various workers in the field.

A modified version of the original Townsend apparatus used by Huxley and his associates (1962) is shown in fig. 1.1a.

Electrons from the filament F are introduced into the drift chamber through the small hole S in the centre of the cathode and proceed through the gas in the Z-direction to the anode as a spreading stream. A uniform electric field E is maintained between the cathode and the anode by use of metal guard rings at the outer boundary of the chamber.

The receiving electrode (anode) is divided into a central strip, separated by narrow gaps from the remaining sections of the anode (fig. 1.1<u>b</u>). All three sections of the anode are insulated from each other but can be combined as receiving electrodes by external electrical connections. The drift velocity measurement is achieved by connecting the central strip electrically to one of the larger sections, so in effect the anode comprises two sections only to which the currents are I_2 and $I_1 + I_3$. A uniform magnetic field, B, can be applied at

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(a)



Fig. 1.1:

Schematic diagram of a Townsend-type apparatus for measuring drift velocity. Receiving electrode. (a)

(b)

right angles to the direction of drift and parallel to the edges of the central strip. If, now, the strength and sense of B are adjusted such that $I_2 = I_1 + I_3$, then the central axis of drift will fall on the gap dividing the currents I_2 and $I_1 + I_3$.

If the direction of the axis of stream makes an angle θ with OZ, then tan $\theta = b/h$, where b is half the width of the central strip and h is the cathode-anode separation.

In the first experiments designed to measure the drift velocity it was assumed that $\tan \theta$ is equal to the ratio of the magnetic force, (eWB) to the electric force on the electron, (eE) yielding

$$\tan \theta = \frac{WB}{E} = \frac{b}{h}$$

i.e.
$$W = \frac{E}{B} \left(\frac{b}{h} \right)$$

This theory is oversimplified because W here does not represent the true drift velocity but a related quantity W_M which is the magnetic drift velocity. Thus if $\tan \theta = \frac{W_x}{W_z}$ where W_x and W_z are the horizontal and vertical components of W, and W_M is defined as

$$W_{M} = \frac{E}{B} \tan \theta$$

then the true value of W is proportional to W_M

i.e.
$$W = C W_M$$

where C is a constant which depends on the electron energy distribution (Huxley and Crompton 1974).

As was pointed out above, the early experiments designed to measure the drift velocity, W, using the Townsend method, measured W_M

instead. The observed difference between the two transport coefficients W and W_M is not always understood. With modern experimental techniques, e.g. time-of-flight methods, the difference between W and W_M is, in general, found to be well in excess of experimental error (Huxley and Crompton 1974).

1.2.2 Electrical Shutter Method

As mentioned in section 1.1, the concept of this method was introduced, independently by Van de Graaff (1928), and Tyndall <u>et al</u>. (1928). These workers devised very similar techniques for the measurement of ion mobilities in gases. The electrical shutter technique was successfully adapted by Bradbury and Nielson (1937), for the measurement of drift velocities. In Bradbury and Nielson's method, the electrical shutters were used to determine the time-of-flight of an electron group through the gas.

The principle of the method is very simple. Electrons produced by UV light (or thermionically) proceeded in a uniform field maintained between the cathode and the collector by a series of guard rings. On their passage from the cathode to the collector electrons traversed two grids accurately separated by a distance, h. Instead of the four gauze system used by Tyndall <u>et al</u>. (1928), Bradbury and Nielson used a coplanar grid arrangement of the form shown schematically in fig. 1.2. In this form of grid the two sets of interconnected wires were mounted on a mica, glass or ceramic former. The two sections of the grid were connected to the output of a high frequency oscillator. Since the mobility of the electrons is much greater than that of the ions, the majority of the electrons were swept to the wires by the alternating field.

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Fig. 1.3 Electrical shutter system used by Phelps <u>et al</u>. (1962); W is a quartz window, S, photocathode, G_1 and G_2 are the two shutters, C is the collector.





Bradbury and Nielson's interpretation of time-of-flight obtained by their electrical shutter system was extremely simple. The first shutter acted simply as a gate which admitted a well defined electron group into the drift region at a known time, while it was supposed that the second shutter could be used to sample the time variation of the electron density at a plane a known distance from the first shutter without disturbing the number density at any time. With these assumptions the transit time of the group was taken as the time interval between the opening of the shutters that corresponded to maximum transmission of the second shutter.

Fig. 1.3 shows a more recent version based on Bradbury and Nielson's electrical shutter system, employed by Phelps, Pack and Frost (1960). In a series of experiments Phelps <u>et al</u>. used UV light, both in the C.W. and pulsed modes, to librate electrons from the photocathode, S. The electrons drifted to the collector, C, under uniform electric field maintained by guard electrodes. The guard electrodes were constructed so that the drift region was shielded electrically from surface charges on the glass wall and, to a large extent, optically from the UV light. The shutters were made of 0.08 mm diameter wire spaced 0.8 mm apart and mounted on fired lava formers which were shielded from electron stream by metal facings. Phelps <u>et</u> <u>al</u>. used rectangular pulse instead of the sine-wave used by Bradbury and Nielson to operate the electric shutters. The disadvantage of sine-wave signals arises from the need, in some circumstances, to use large amplitudes to achieve adequate resolution.

When the C.W. source was used, the first grid provided a time varying electron current (i.e. it was used to inject electrons into the drift region), and the second grid was used to measure the transit time

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of the electrons from the first grid. The value of W was determined from this measurement and the drift distance h. With a pulsed UV source, either of the two grids could be employed for measurement of transit time of the electrons from the photocathode (i.e. both grids could serve as the sampling grid). The time required by the electrons to travel between the two grids was determined from the difference in transit times from the photocathode to the respective grids. The idea of this differencing procedure was to eliminate end-effects.

In one mode of operation Pack and Phelps (1961); Pack and Voshall (1962) applied a DC bias voltage between the two halves of the first grid such that the transmitted electron current was reduced by about 10% of its values with zero bias, while the second grid was passive. The transmitted electron current could be maximized with the aid of a rectangular pulse applied to each half of the grid at a certain time, t, after the UV pulse. By varying this delay, t, between the voltage pulse applied to the first grid and the UV pulse, the time distribution of the collector current for one position could be found. Similarly, by making the first grid passive and the second grid active, the time distribution of collector current could be found for another position. This situation is represented schematically in fig. 1.4. The drift velocity is found from the relation,

$$W = \frac{h}{t_2 - t_1}$$

In another mode of operation, Pack, Voshall and Phelps (1962) used a modified procedure which they called the "zero bias" or "rejection" mode. In this method the two halves of the grid were held at the same potential except during the short time interval in which a rectangular pulse was applied to reduce its transmission. As a result minimum current was received by the collector when the application of the pulse coincided with the arrival of the electron group from the photocathode. The operation of the shutter in this way results in the field in the drift region being maintained free of distortion except during the short time interval in which the flux through the shutter is sampled.

1.2.3 The Pulse Method(s)

The third basic concept for measuring drift velocities of electrons in gases is that of the pulse methods. In these methods W is determined from measurement of arrival time distributions. There have been several variations of the pulse method. These may be classified according to the mode of electron pulse production (i.e. fission fragments, α -particles, β -particles, X-rays and UV light). The common factor between all cases is that electrons are created suddenly and the drift velocity is determined from a measurement of the time taken by free electrons to travel a known distance to the detector.

Perhaps the most significant among the pulse methods is the technique adopted by the group at Oak Ridge National Laboratory (ORNL). This group developed a technique, (initially introduced in the early 1960's), which enables measurements of both drift velocities and diffusion coefficients to be made simultaneously. This technique depends on detection of the time-of-flight of a single electron.

Fig. 1.5 shows a schematic diagram of the experimental system used by the ORNL group following a series of modifications reviewed in a paper by Wagner, Davis and Hurst (1967). The main vacuum chamber is divided into three sections, a swarm region, transition region and detection region connected only by small apertures. With this arrange-

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Fig. 1.5 Time-of-flight apparatus of Wagner et al. (1967).



Fig. 1.6 Block diagram of the electronic system associated with the time-of-flight apparatus of Wagner <u>et al.</u> (1967).

ment and the use of high speed pumps to evacuate the transition and detection regions, pressures from 1 to 25 torr could be used in the swarm region while maintaining a pressure of the order 10^{-6} torr in the detection region, thereby enabling an electron multiplier to be employed as the detector. In their initial work, Hurst <u>et al</u>. (1963) used a counter operating in the G-M mode as a detector, as a consequence time-of-flight measurements were restricted to gases and gas pressures suitable for the operation of such detectors.

Large-diameter guard rings were used to form a drift chamber of 24.5 cm length in which a uniform electric field could be established. Electrons were generated by pulses of UV light passing through a quartz window onto a photocathode. The UV pulses were produced by an EG and G xenon filled flash tube type FX-6U. Pulse durations of the order 275 nsec and repetition rates of about 300 s^{-1} were used. This pulse was monitored by an EG and G photodiode type SD100.

Fig. 1.6 shows a block diagram of the electronic logic used in (Hurst and Parks - 1966) time-of-flight experiments. The signal from the photodiode, caused by a flash from the pulsed UV light source, serves as the starting signal for the time-of-flight analyser, which consists of a time-to-voltage-amplitude converter and a multichannel analyser. The stop signal is derived from an output pulse from the electron multiplier caused by an electron arriving at the collector. Each event is recorded in the appropriate channel of the analyser, and the experiment proceeds until adequate statistics are obtained. The channel width of the analyser can be varied from 31.25 nsec to 64 µsec.

The theory of method described above, as given by Hurst and Parks (1966), can be understood by referring to the schematic diagram representing the apparatus shown in figure 1.7. A uniform electron distribution

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is established momentarily over the plane x = 0 at time t = 0, and the electron concentration is sampled subsequently at the aperture P (of area a) as a function of time. Assuming that there are no sources or sinks of electrons and in the absence of ionization and attachment, the differential equation applicable to the geometry of fig. 1.7 is

$$\frac{\partial n}{\partial t}(x,t) = D_{L} \frac{\partial^{2} n}{\partial x^{2}}(x,t) - W \frac{\partial n}{\partial x}(x,t) \qquad [1.1]$$

where D_L is the longitudinal diffusion coefficient, (it is now recognised that the study of arrival time spectra yield data for D_L rather than the isotropic diffusion D), and n(x,t) is the electron number density at a time t, and at a distance x measured along the direction of the drift field E. A solution of equation 1.1 ignoring the diffusion to the electrodes at x = 0 and x = d is

$$n(x,t) = N_o(4\pi D_L t)^{-\frac{1}{2}} \exp\left[-\frac{(x-Wt)^2}{4D_L t}\right]$$
 [1.2]

where N_o is the number of electrons per unit area at the cathode at t=0.

The number of electrons $E(t)\Delta t$ arriving from the cathode to the aperture (of area a) of the detector between t and $t + \Delta t$ can be found by assuming that the diffusion is negligibly small. With this assumption, the rate of arrival of electrons at P is

$$E(t) \Delta t = Wan(d,t)$$

that is

$$E(t)\Delta t = Wa N_{o}(4\pi D_{L}t)^{-\frac{1}{2}} \exp\left[-\frac{(d-Wt)^{2}}{4D_{L}t}\right]\Delta t \qquad [1.3]$$

The maximum value of E(t) occurs when

$$\frac{\partial E}{\partial t}(t) = 0$$

i.e.

$$-\frac{E(t)}{2t} + \left[\frac{2W(d-Wt)}{4D_{L}t} + \frac{(d-Wt)^{2}}{4D_{L}t^{2}}\right]E(t) = 0$$
 [1.4]

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But to a first approximation $W \simeq \frac{d}{t_m}$

where t_m is the time at which maximum E(t) is recorded.

Therefore

 $W^2 t_m^2 + 2D_L t_m - d^2 = 0$

or

 $d - Wt_{m} = \frac{2D_{L}t_{m}}{d + Wt_{m}}$

putting $d \simeq Wt_m$

then

$$d - Wt_m \simeq \frac{D_L}{W}$$

that is

$$W \simeq \frac{d}{t_m} \quad (1-\beta)^*$$
 [1.5]

* Equation 1.5 was stated in a different form by Wagner et al. as:

$$W = \frac{d}{t_{m}} (1 + \beta^{\frac{1}{2}} + \cdots)^{-1} \text{ where } \beta^{\frac{1}{2}} \simeq \frac{D_{L}}{Wd} \text{ i.e. } \beta^{\frac{1}{2}} \equiv \beta$$

It follows that the two equations are equivalent.

where $\beta = \underline{D_L}$ is the first order correction factor. Wd

In addition to this correction, Hurst <u>et al</u>. made an elaborate analysis accounting for the electronic fluctuations and the distortion in the spectrum resulting from the dead time of the detection system (these will be considered in chapter 3).

1.2.4 W measurement by detection of photons from drifting electrons

One technique for measuring W that can not be included in any of the three basic classes mentioned above, is that of Breare and Von Engel (1964). The reason for mentioning this technique is that these authors have used a novel approach which is fundamentally different from the other ones described. The principle of the technique of Breare and Von Engel is based upon locating the position of a drifting electron group from photons emitted by gas molecules excited by the electron swarm. (For details of the apparatus and experiment see the original reference.)

In general, an optical method for determining the transport coefficients of electrons in gases requires carrying out the experiments at very low pressures. This is necessary to eliminate radiation imprisonment which may result in resonances as well as excitation transfer processes. Thus one obvious advantage of the method of Breare and Von Engel is that it enables measurements to be carried out at very high E/p values with less likelihood of extraneous breakdown.

1.3 Measurement of D/W and D_L

Unlike W, measurements of D/W, the ratio of drift velocity to diffusion coefficient, and the longitudinal diffusion D_L , have been

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carried out by fewer experimental techniques. Basically there are two methods for the measurement of these quantities.

- (1) The Townsend method which allows determination of W/D.
- (2) The time-of-flight method which yields the longitudinal diffusion coefficient D_L .

The theoretical methods of the two techniques are rather different. The Townsend method uses a steady-state point source and a plane detector. In contrast the time-of-flight method utilizes a pulsed plane source and a point detector. In the Townsend method the quantity D/W is measured as a function of a ratio R, of two currents, whereas in the time-of-flight method, the longitudinal diffusion D_L is obtained from the distribution of arrival times of electrons. Furthermore, the theoretical argument upon which D_L measurements is based, depends on solving the Boltzmann transport equation in one dimension rather than three dimensions as in the Townsend method.

1.3.1 The Townsend lateral diffusion method

A modern form of Townsend's apparatus used by Huxley <u>et al</u>. (1962) for measuring the ratio D/W is shown in figure 1.8<u>a</u>. Electrons are emitted continuously from the filament F. They pass through the aperture 0 (~1 mm diameter), and drift to the anode diffusing in their passage through the chamber in a uniform electric field established throughout the cylindrical volume by guard electrodes. While the plane containing the aperture 0 forms one boundary of the diffusion chamber, the anode A forms the other boundary. The anode is divided with axial symmetry into a central disc, A, of radius b, and an annulus A₂ radius c, as shown in figure 1.8<u>b</u>. The two boundaries are accurately separated by a distance h. The experiment consists of determining the distribu-



tion of current at the anode by measuring the currents at A_1 , I_b and at A_2 , I_c for a given E/p value. The ratio ^W/D is then found from the solution of the appropriate three dimensional time dependent diffusion problem which yields

$$R = 1 - \frac{h}{d} e^{-\lambda(d-h)}$$

where R is the current ratio $\frac{I_b}{I_b + I_c}$,

 $d = (h^2 + b^2)^{\frac{1}{2}}$

and

$$\lambda = \frac{W}{2D}$$

A number of problems arising from boundaries, contact potential differences, space charge effects, uniformity of drift field, and other factors affecting the accuracy of measurement have been discussed in detail by Crompton <u>et al.</u> (1965).

Different solution for R, corresponding to a number of theoretical models devised by various workers are discussed in detail in Huxley and Crompton (1974).

1.3.2 The time-of-flight method

Details of experiments based on this method as given by Hurst <u>et</u> <u>al</u>. (1966) are outlined in section 1.2.3 and therefore need not be repeated here. Hence, the discussion in this section will be restricted to the evaluation of longitudinal diffusion from the arrival time distributions.

We have seen that, (see section 1.2.3), by assuming that the



diffusion to the electrodes is negligible (i.e. $D_L/W \ll 1$), the number of electrons E(t) Δ t arriving at the detector, distance, d from the photocathode, between t and t+ Δ t is given by (equation 1.3)

$$E(t)\Delta t = N_0 aW\Delta t (4\pi D_L t)^{-\frac{1}{2}} exp\left[-\frac{(d-Wt)^2}{4D_L t}\right]$$
[1.6]

where D_L is the longitudinal diffusion. The drift velocity, W can be calculated to first approximation from

$$W \simeq \frac{d}{t_m}$$

where t_m is the time at which maximum E(t) occurs.

Now, referring to figure 1.9 which represents a time of arrival distribution, if t_1 is the time at which the value of E(t) is 1/e of its value at t_m , then by substituting into equation 1.6 it can be shown that

$$t_1 \simeq \frac{d}{W} (1 + 2\beta^{\frac{1}{2}})$$

provided that $2\beta^{\frac{1}{2}} \ll 1$ where β , as before = $\frac{D_L}{Wd}$. If δt is defined as

$$\delta t = t_1 - t_m$$
 then

$$\delta t \simeq 2 \left(\frac{\mathrm{d} \mathrm{D}_{\mathrm{L}}}{\mathrm{W}^3} \right)^{\frac{1}{2}}$$

From arrival time distribution δt can be found and hence D_{L} can be determined from

$$D_{L} \simeq \frac{d^{2} \delta t^{2}}{4 t_{m}^{3}}$$

A more exact value of D_{L} as given by Wagner, Davis and Hurst is

$$D_{L} = \frac{d^{2} \delta t^{2}}{4 t_{m}^{3}} (1 - 2\beta)$$

CHAPTER 2

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THEORY

2.1 The Maxwell-Boltzmann Equation

The Maxwell-Boltzmann equation is fundamental and constitutes one of the basic foundations of almost all theoretical and rigorous mathematical descriptions of electron motion in gases. It is, therefore, convenient to begin this chapter by formulating the Maxwell-Boltzmann equation in a general form as a six dimensional equation of continuity in phase space.

Consider a system of gas molecules and electrons. Suppose that the system is in thermal equilibrium. Let the molecules and electrons have masses M and m and number densities N and n respectively. The number density N of the gas molecules is independent of position and everywhere very much greater than the number density n of the electrons which, in general, is a function of position and time and written as $n(\mathbf{r}, \mathbf{t})$ (often denoted simply by n).

The number of electrons within an element of volume dr of configuration space at vector position \mathbf{r} and time t is $n(\mathbf{r},t)d\mathbf{r}$. The velocities \mathbf{c} of the $n(\mathbf{r},t)d\mathbf{r}$ electrons range widely in magnitude and direction. Therefore it is convenient to associate a velocity space with the configuration space in order to account for the motion of the group of $n(\mathbf{r},t)d\mathbf{r}$ as a whole. In velocity space, velocity \mathbf{c} is represented by a point, its velocity point, which is the end point in this space of the vector \mathbf{c} . Therefore, the motion of the $n(\mathbf{r},t)d\mathbf{r}$ electrons in configuration space is represented by $n(\mathbf{r},t)d\mathbf{r}$ velocity points in velocity space.

In an elementary region $d\underline{c}$ of velocity space at vector position \underline{c} ,

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the number of electrons at time t that lie within the volume element $d\underline{r}$ at \underline{r} , and whose velocity points lie also within the elementary region $d\underline{c}$ of velocity space, is designated $[n(\underline{r},t)d\underline{r}][f(\underline{r},\underline{c},t)d\underline{c}] \equiv nf d\underline{r} d\underline{c}$. The function $f(\underline{r},\underline{c},t)$ is the general velocity distribution function.

The product nf is a fundamental quantity in formulating Maxwell-Boltzmann equation. The differential equation which is satisfied by nf, is the Maxwell-Boltzmann equation of continuity for the population nf d<u>r</u> d<u>c</u> electrons. [These electrons will be referred to as the class nf d<u>r</u> d<u>c</u>.]

The rate of change of the population of the class $nf d\underline{r} d\underline{c}$ is

$$\frac{\partial}{\partial t}$$
 (nf) dr dc

This rate of change results from three processes:

(i) A loss of population due to the transport of electrons across the boundary surface of the elementary volume $d\underline{r}$ in configuration space. Since $d\underline{r}$ is immersed in the beam of $d\underline{c}$ and from the fact that of, in general, is not constant along or across the beam, it follows that there is a net loss of electrons in time dt equal to

div_r (cnf) dr dc dt,

where $\operatorname{div}_{\mathbf{r}}$ is the divergence operator in configuration space.

(ii) Electrons move at constant velocities between encounters with the gas molecules in the absence of an electric field and hence their velocity points remain at rest in velocity space. However, in the presence of an electric field <u>E</u>, an acceleration eE/m is imparted to each of the ndr electrons whose velocity points, as a result, all drift in velocity space at a common rate eE/m. There is, therefore, a net loss of velocity points from the elementary region dc, by drift across

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the surface. The number of points lost in time dt from $d\underline{c}$, which is a loss of population from the class of $d\underline{r}$ d \underline{c} , is equal to

dt div_c
$$\left(\begin{array}{c} \text{nf } \underline{e\underline{E}} \\ \underline{m} \end{array} \right) d\underline{r} \ d\underline{c}$$

where div_c is the divergence operator in velocity space.

(iii) Points are also lost from dc because of the quasi discontinuous changes in position Δc in velocity space that occur when an electron encounters a molecule. These discontinuous changes in velocity remove points from dc to another region of velocity space. In addition dc receives points through displacements Δc , due to encounters, from other elements dc of velocity space. The net loss, which is the excess of the loss over the gain in time dt, is written as

S d<u>c</u> d<u>r</u> dt

Therefore the rate of change of population of the class of $d\underline{c} d\underline{r}$ may be written as

$$\frac{\partial}{\partial t} (nf) d\underline{c} d\underline{r} dt = - \operatorname{div}_{\mathbf{r}} (nf\underline{c}) d\underline{c} d\underline{r} dt - \operatorname{div}_{\mathbf{c}} \left(nf \frac{e\underline{E}}{m} \right) d\underline{c} d\underline{r} dt$$

$$- S dc dr dt$$

or

$$\frac{\partial}{\partial t} (nf) + \operatorname{div}_{\mathbf{r}}(nf\underline{c}) + \operatorname{div}_{\mathbf{c}}\left(nf \ \underline{e\underline{E}}{\underline{m}}\right) + S = 0 \qquad [2.1]$$

Equation [2.1] is the basic Maxwell-Boltzmann transport equation, describing the motion of electrons in gases.

2.2 Huxley and Crompton Formulation of the Transport Equation

Equation 2.1 is the fundamental Maxwell and Boltzmann equation derived in a general form as a six dimensional equation of continuity to be satisfied by the quantity nf, i.e. the product of the number density of electrons and their velocity distribution function.

In order to evaluate the transport coefficients of electrons in gases, Huxley and Crompton (1974) have used equation 2.1 to develop a pair of working equations to achieve that goal. The two equations which they termed the scalar and the vector equations represent the conservation of energy and momentum respectively.

Huxley and Crompton considered a thin shell of velocity space bounded by spherical surfaces c and c + dc with the origin at the centre. For this shell, which is denoted (c,dc), they assumed that the velocity distribution function f may be represented by a convergent series of the form

$$f(c,\theta,\underline{r},t) = f_0(c,\underline{r},t) + \sum_{k=1}^{\infty} f_k(c,\underline{r},t) P_k(\cos \theta), \quad [2.2]$$

in which $P_k(\cos \theta)$ is the kth order Legendre polynomial. Then they have used this assumption in equation 2.1 adapted for a complete shell of phase space (i.e. covering both configuration and velocity spaces) to derive their scalar and vector equations.

For the scalar equation Huxley and Crompton have used a transformation which enables equation 2.1 at the outset to be direction independent. By replacing the class $(nf)d\underline{r} d\underline{c}$ by the class $(nf_0)d\underline{r}$ $(4\Pi c^2 dc)$, using the expansion of equation 2.2 and following a similar treatment for the processes involved in rate of change of population discussed in section 2.1, they obtained a scalar equation of the form

$$\frac{\partial}{\partial t} (nf_0) + \frac{c}{3} \frac{div_r(nf_1)}{4\pi c^2} + \frac{1}{4\pi c^2} \frac{\partial}{\partial c} [\sigma_E(c) - \sigma_{coll}(c)] = 0$$

[2.3]

in which

$$\sigma_{\mathbf{E}}(\mathbf{c}) = \frac{4\Pi c^2}{3} \frac{e\underline{E}}{m} \cdot n \underline{f}_1 \qquad [2.4]$$

$$\sigma_{coll}(c) = 4 \Pi n \ c^2 \ v_{el} \left(\frac{m}{M} \ cf_0 + \overline{C^2} \ \frac{\partial f_0}{\partial c} \right)$$
[2.5]

where

 \underline{f}_1 is a vector with magnitude $f_1 \equiv f_1(c,\underline{r},t)$ and direction parallel to the axis whose polar angle $\theta = 0$; v_{e1} is the collision frequency of elastic encounters, $v_{e1} = Ncq_{m_{el}}(c)$ and $\overline{C^2}$ is the mean-square speed of the gas molecules. N and M are the molecular number density and mass respectively and $q_{m_{el}}(c)$ the momentum transfer cross section for elastic collisions.

In order to determine the two dependent variables nf_0 and nf_1 in equation (2.3), a second relationship between them is required. This second relationship is the vector equation mentioned earlier. The vector equation is an independent equation obtained by considering the momentum of the electrons of the shell (c,dc). It is formulated for the class by considering the processes that operate to change the momentum. Using the expansion of equation (2.2) Huxley and Crompton assumed that $f_0 \gg f_1 > f_2$ and thus omitted f_2 for simplification (this assumption is not valid in general as will be shown in section 2.7). The vector equation they have obtained reads

$$\frac{\partial}{\partial t} (n\underline{f}_1) + c \operatorname{grad}_{\mathbf{r}}(n\underline{f}_0) + \underbrace{e\underline{E}}_{\overline{m}} \frac{\partial}{\partial c} (n\underline{f}_0) + \sqrt{n}\underline{f}_1 = 0 \quad [2.6]$$

The scalar and vector equations stated above describe the motion of electrons in gases in the presence of an electric field E. In these equations only elastic collisions are considered.

2.2.1 The influence of inelastic encounters on the scalar and vector equations

The quantity $\sigma_{coll}(c)$ given in equation (2.5) represents the contribution of elastic encounters only. The presence of inelastic encounters requires modifications to be made on the constituent terms of the scalar and vector equation. There are two such modifications: firstly, terms to account for inelastic encounters should be supplemented to the expression for $\sigma_{coll}(c)$. Secondly, the presence of inelastic encounters makes the momentum transfer cross-section $q_m(c)$ a composite cross-section representing loss of momentum both in elastic encounters and encounters that are not elastic.

To find the contribution of the inelastic encounters consider a hypothetical model gas whose molecules possess a single energy state other than the ground state and therefore a single threshold energy for an inelastic encounter. Assume that all molecules are in the ground state so that superelastic encounters are absent.

For a group of electrons n_0 , the contribution to $\sigma_{coll}(c)$ from elastic encounters, (assuming that $f_0(c)$ and $\sigma_{coll}(c)$ relate to the whole group), is (equation 2.5)

$$\sigma_{\text{coll}}(c) = 4 \Pi n_0 c^2 v_{\text{el}} \left(\frac{m}{M} c f_0 + \overline{C^2} \frac{d}{dc} f_0 \right)$$
 [2.7]

For the contribution of inelastic encounters let ε_{in} be the threshold energy in the model gas, and $q_{o_{in}}(c)$ be the total inelastic collision cross section. Then, the speed of an electron with energy ε_{in} is

$$c_{in} = \left(\frac{2\varepsilon_{in}}{m}\right)^{\frac{1}{2}}$$
 [2.8]

Since $q_{o_{in}}(c)$ is zero when the speed c of an electron is less than c_{in} ,



 $c''^2 = c'^2 - c_{in}^2$ $c < c_{in}$

(a)



(b)

Fig. 2.1 Influence of inelastic cross-sections on the scaler and vector equations.

 $q_{o_{in}}$ may be expressed in the form $q_{o_{in}}(c)I(c - c_{in})$, where I is the unit step function. The number of inelastic encounters made in time dt by electrons whose velocity points lie in the shell (c,dc) is $(4\pi n_0 f_0 c^2 dc)$ $[Ncq_{o_{in}}(c)]dt$.

Consider the spherical surfaces (fig. 2.1) in velocity space. Let the speeds of an electron before and after an elastic encounter be c' and c", then if the change in the translational energy of the molecule is neglected it follows that $\varepsilon_{in} = \frac{1}{2} m (c'^2 - c''^2)$

i.e.

$$c''^2 = c'^2 - \frac{2\varepsilon_{in}}{m}$$

$$= c'^{2} - c_{in}^{2}$$
, $c' > c_{in}$

The necessary condition for a velocity point to move from a position outside to a position inside a sphere c is that $c' \leq c \leq c'$. Two cases arise.

(a) c < c_{in} (Fig. 2.1a)

For a velocity point to be displaced from outside to inside the sphere c, its initial position must lie within the region bounded by the spheres with radii c_{in} and $c_1 = (c^2 + c_{in}^2)^{\frac{1}{2}}$, and it follows that the number of points that cross the surface c in time dt is

dt .
$$4 \Pi n_0 N \int_{c_{in}}^{c_i} f_0(x) x^3 q_{o_{in}}(x) dx$$
,

Consequently, with case (a), the contribution from inelastic encounters to $\sigma_{coll}(c)$ is

$$\sigma_{coll_{in}}(c) = 4 \Pi n_0 N \int_{c_{in}}^{c_i} f_0(x) x^3 q_{o_{in}}(x) dx$$
 [2.9]

(b) $c > c_{in}$ (Fig. 2.1b).

It can be seen that in this case the expression for $\sigma_{coll_m}(c)$

is

$$\sigma_{coll_{in}}(c) = 4 \Pi n_0 N \int_{c}^{c_i} f_0(x) x^3 q_{o_{in}}(x) dx$$
 [2.10]

Equations (2.9) and (2.10) can be included in a single expression using the form of $q_{o_{in}}(c)$, mentioned earlier, to give

$$\sigma_{\text{coll}_{in}}(c) = 4 \Pi n_0 N \int_c^{c_i} f_0(x) x^3 q_{o_{in}}(x) I (x-c_{1n}) dx$$

The total flux is therefore

$$\sigma_{coll}(c) = \sigma_{coll_{el}}(c) + \sigma_{coll_{in}}(c)$$

$$= 4 \Pi n_0 N \left[c^3 q_{\mathbf{m}_{el}}(c) \left(\frac{m}{M} c f_0 + \frac{\overline{C^2}}{3} \frac{d}{dc} f_0 \right) + \int_c^{c_1} f_0(x) x^3 q_{o_{in}}(x) I(x - c_{in}) dx \right]$$
[2.11]

The differential equation for $f_0(c)$ [using the values of $\sigma_E(c)$ and $\sigma_{coll_{el}}(c)$] is, for the steady state,

$$- \frac{eE}{mv_{el}} \cdot \frac{f_1}{m} + \frac{C^2}{c^2} \frac{df_0}{dc} + \frac{3m}{M} \frac{cf_0}{c^3 q_{m_{el}}(c)} + \frac{3}{c^3 q_{m_{el}}(c)} \int_c^{c_1} f_0(x) x^3 q_{o_{in}}(x) I(x - c_{in}) dx = 0$$
[2.12]

Equation (2.12) is the scalar equation for the model gas.

The vector equation is obtained by finding an expression for the function $\underline{f}_1(c)$. \underline{f}_1 can be found by considering the momentum contributions of the electrons of the shell (c,dc), i.e. by considering the processes that increase or decrease the momentum. Three such processes are present in this case:

(i) Loss of momentum through inelastic encounters, in which event electrons are removed from the shell (c,dc) to another region of velocity space. The momentum lost in time dt by the group is expressed

dt
$$\left(\frac{4\pi}{3} n_{o} c^{3} dc\right) \underline{mf}_{1}(c) \operatorname{Ncq}_{o_{in}}(c) I(c-c_{in})$$

(ii) Gain of momentum through inelastic encounters; velocity points are transferred by inelastic encounters from a shell (c_1,dc_1) to the shell (c,dc). In such an event the group of electrons from (c_1,dc_1) will retain a fraction of their momentum. The momentum retained by the electrons scattered inelastically from the shell (c_1,dc_1) in time dt and therefore transferred to the shell (c,dc) is

dt
$$\left(\frac{4\pi}{3} n_0 m\right) \left[Nc_1 q_{1_{in}}(c_1) \right] \underline{f}_1 (c_1) c_1 c^2 dc$$
.

(iii) Gain of momentum from the force eE given by

$$- \operatorname{dt} \frac{4\Pi}{3} \operatorname{n}_{o} \operatorname{e} \underline{\mathrm{E}} \operatorname{c}^{3} \frac{\operatorname{df}_{0}}{\operatorname{dc}} \operatorname{dc} .$$

On assembling the gains and losses of momentum, the following equation for the state of equilibrium is obtained for $f_1(c)$:

$$- \underline{e\underline{E}}_{\overline{m}} \frac{d}{dc} f_{0} = \left[v_{el} + v_{Oin} I(c-c_{in}) \right] \underline{f}_{1}(c) - \left[Nc_{1}q_{1in}(c_{1}) \frac{c_{1}}{c} \underline{f}_{1}(c_{1}) \right].$$

$$[2.13]$$

Equation (2.13) can be rewritten as

$$\underline{f}_{1}(c) = - \underbrace{e\underline{E}}_{m[\nu_{el} + \nu_{Oin}I(c-c_{in})]} \frac{d}{dc} f_{0}(c)$$

$$+ \underbrace{q_{1in}(c_{1})}_{q_{m_{el}}(c) + q_{Oin}(c) I(c-c_{in})} \frac{c_{1}}{c}^{2} \underline{f}_{1}(c_{1}) \qquad [2.14]$$

A simplifying assumption can be made to omit the term depending

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as

upon c_1 since its presence represents a complication. A case in which its omission is justified occurs when the inelastic scattering is isotropic. In such a case, the term may be omitted as small (compared with the first term on the RHS of equation 2.14) on the grounds that $q_{m_{el}}(c)$ is much greater than $q_{oin}(c)$ and $q_{1in}(c)$ over a useful range of speeds c.

Under these conditions $f_1(c)$ may be rewritten as

$$\underline{f}_{1}(c) = -V' \underline{d}_{dc} f_{0}(c)$$
 [2.14]

where

$$V' = \frac{eE}{mv}$$
.

v is the effective collision frequency given by $v = v_{el} + v_{O_{in}}I(c-c_{in})$ when inelastic scattering is isotropic. Note this is not valid in general (see section 2.7).

It follows from equation (2.12), that, in the general case, the scalar equation becomes

$$(VV' + \overline{C^2}) \frac{d}{dc} f_0 + \frac{3m}{M} f_0 + \frac{3}{c^3 q_{m_{el}}(c)} \int_c^{c_1} f_0(x) x^3 q_{o_{in}}(x) I(x-c_{in}) dx = 0$$
[2.15]

2.2.2 The influence of superelastic encounters

In the preceding argument the contribution of superelastic encounters has been neglected on the assumption that all molecules of the hypothetical model gas are in the ground state. This assumption is, in general, justified provided that the smallest threshold energy for inelastic encounters greatly exceeds kT as in monoatomic gases. In molecular gases, however, the threshold energies for changes in rotational energies of molecules are comparable in magnitude with kT at room temperatures, and the number of molecules in rotational states other than the ground state is an appreciable proportion of the whole.

Let N_o be the number density of molecules in the ground state; then the number in the state with the threshold energy ε_{in} is N_o exp ($-\varepsilon_{in}/kT$). In some encounters between electrons and molecules in the excited state, the molecules revert to the ground state and the energy ε_{in} is communicated to the electrons. Such encounters are superelastic.

Let c' and c' be, respectively, the speeds of an electron before and after a superelastic encounter; then $\frac{1}{2}m(c'^2 - c'^2) = \varepsilon_{in} = \frac{1}{2}mc_{in}^2$. Consider the sphere c of velocity space; let $c_2^2 = c^2 - (\frac{2\varepsilon_{in}}{m}) = c^2 - c_{in}^2$. Then two cases arise:

(a) $c < c_{in}$

The number of superelastic encounters made by the $4 \Pi n_0 f_0$ (x) $x^2 dx$ electrons of the shell (x,dx) in time dt is

dt $4 \Pi n_0 [Nxq_{0s}(x)] f_0(x) x^2 dx$

where $q_{o_s}(x)$ is the total superelastic collision cross section. [Note that in superelastic encounters the velocity point of the electron is displaced away from the origin of velocity space and hence these encounters give rise to an outward flux of points across the sphere c in contrast to inelastic encounters, which maintain an inward flux.]

$$4 \Pi n_{o} N \int_{o}^{c} f_{0}(x) x^{3} q_{o}(x) dx .$$

(b) $c > c_{in}$

For this case the outward flux from superelastic encounters across the surface of the sphere c is

$$4 \Pi n_{0} \, N \, \int_{c_{2}}^{c} \, f_{0} (x) \, x^{3} \, q_{0_{s}}(x) \, dx \, .$$

Therefore rewriting equation (2.11) to include the contribution, to σ_{coll} , of superelastic encounters we get

$$\sigma_{coll} = 4 \Pi n_{o} \left\{ Nc^{3} q_{m_{el}}(c) \left(\frac{m}{M} cf_{0} + \frac{\overline{C^{2}}}{3} \frac{d}{dc} f_{0} \right) + N \left[\int_{c}^{c_{1}} f_{0}(x) x^{3} q_{o_{in}}(x) I(x - c_{in}) dx - \int_{o \text{ or } c_{2}}^{c} f_{0}(x) x^{3} q_{o_{s}}(x) dx \right] \right\}$$
[2.16]

in which the lower limit in the second integral is zero when $c < c_{in}$ but c_2 when $c > c_{in}$.

In our model gas only a single kind of inelastic encounter has been considered. In actual gases in general, however, a variety of inelastic encounters, associated with transitions between many pairs of energy states, may occur. Therefore, to account for this fact the scalar and vector equations should be modified. The scalar equation takes the form

$$-c^{2} \frac{eE}{3m} \frac{f_{1}}{m} + Nc^{3}q_{m_{el}}(c) \left(\frac{mc}{M} f_{0} + \frac{\overline{C^{2}}}{3} \frac{d}{dc} f_{0}\right) + N\sum_{k} I_{k} = 0 \qquad [2.17]$$

where

$$I_{\mathbf{k}} = \int_{c}^{c_{1}\mathbf{k}} \left[f_{0}(\mathbf{x}) - f_{0}\left(\sqrt{\mathbf{x}^{2} - c_{\mathbf{k}_{in}}^{2}}\right) \exp\left(-\frac{\varepsilon_{\mathbf{k}_{in}}}{kT}\right) \right] \mathbf{x}^{3} q_{\mathbf{o}_{\mathbf{k}_{in}}}(\mathbf{x}) I(\mathbf{x} - c_{\mathbf{k}_{in}}) d\mathbf{x} ,$$
[2.18]

in which $\varepsilon_{\mathbf{k}_{in}}$ is the threshold energy required to excite the kth inelastic transition, $c_{\mathbf{k}_{in}}^2 = \frac{2\varepsilon_{\mathbf{k}_{in}}}{m}$, $c_{1\mathbf{k}}^2 = c_{\mathbf{k}_{in}}^2 + c^2$ and $q_{\mathbf{o}_{\mathbf{K}_{in}}}(\mathbf{c})$ is the collision cross section for the kth inelastic transition. The summation over k implies that the relevant inelastic encounters associated with changes in rotational, vibrational and electronic changes of state are included.

The modified vector equation can be written, as before

$$\underline{f}_{1}(c) = - \underbrace{\underline{eE}}_{mv} \underbrace{d}_{dc} f = - V' \underbrace{d}_{dc} f_{0}$$
[2.19]

where v is the effective collision frequency. In the presence of inelastic, superelastic as well as elastic encounters, and on the assumption that inelastic encounters are isotropic (i.e. $q_{1_{\mathbf{k}_{in}}}$ and $q_{1_{\mathbf{k}_s}}$ are zero or negligible), the effective collision frequency may be written as

$$v = v_{e1} + \sum \left[v_{o_{in}} \quad I(c - c_{k_{in}}) + v_{o_s} \right]$$
[2.19]

where $v_{el} = Ncq_{m_{el}}(c)$, $v_{o_{K_{in}}} = Ncq_{o_{K_{in}}}$ and $v_{o_{K_s}} = Ncq_{o_{K_s}}$. When the expression for $f_1(c)$ (equation 2.19) is used in equation 2.17, the scalar equation becomes

$$(VV' + \overline{C^2}) \frac{d}{dc} f_0 + \frac{3m}{M} f_0 + \frac{3}{c^3 q_{m_{el}}(c)} \sum_{k} I_k = 0$$
, [2.20]

which the differential equation (cf. equation 2.15) satisfied by the velocity distribution function $f_0(c)$ for the group n_0 as a whole.

2.3 The Working Scalar Equation

By changing the interpretation of $f_0(c)$ and $\underline{f}_1(c)$ from that of the distribution functions of a group of electrons to that of local distribution functions $f_0(c,\underline{r},t)$ and $\underline{f}_1(c,\underline{r},t)$ (section 2.2), the vector equation and the working scalar equation will be readily obtained.

Rewriting the scalar equation (equation 2.3)

$$\frac{\partial}{\partial t} (nf_0) + \frac{3}{c} \operatorname{div}_{\mathbf{r}}(n\underline{f}_1) + \frac{1}{c^2} \left(\frac{\partial}{\partial c} \frac{c^2}{3} \frac{e\underline{E}}{\underline{m}} \cdot n\underline{f}_1 - \frac{1}{4\underline{II}} \sigma_{\mathbf{coll}} \right) = 0$$
[2.21]

here
$$\frac{1}{4\pi} \sigma_{coll} = c^2 v_{el} \left[\frac{m}{M} cnf_0 + \frac{\overline{C}^2}{3} \frac{\partial}{\partial c} (nf_0) \right] + nN \sum_{\mathbf{k}} I_{\mathbf{k}}$$

and I_k is as given by equation (2.18).

The vector equation, for quasi equilibrium may be written as

$$- n\underline{f}_{1} = \underline{c} \operatorname{grad}_{\mathbf{r}}(nf_{0}) + \underline{eE} \frac{\partial}{\partial c} (nf_{0})$$

$$[2.22]$$

where v is the effective collision frequency for momentum transfer.

The working scalar equation can be obtained by putting the value of nf_1 from equation (2.22) into equation (2.21). Hence

$$\frac{\partial}{\partial t} (nf_{0}) - div_{\mathbf{r}} \left[\frac{c^{2}}{3v} \operatorname{grad}_{\mathbf{r}} (nf_{0}) + \frac{c}{3} \frac{V'}{\partial c} (nf_{0}) \right]$$
$$- \frac{1}{c^{2}} \frac{\partial}{\partial c} \left\{ \frac{c^{3}}{3} \frac{V'}{s} \operatorname{grad}_{\mathbf{r}} (nf_{0}) + \frac{c^{2}v_{e1}}{3} \frac{VV'}{\partial c} (nf_{0}) \right\}$$
$$+ c^{2}v_{e1} \left[\frac{m}{M} c(nf_{0}) + \frac{\overline{C^{2}}}{3} \frac{\partial}{\partial c} (nf_{0}) \right] - \frac{nN}{c^{2}} \sum_{\mathbf{k}} \left(\frac{\partial}{\partial c} I_{\mathbf{k}} \right) = 0 \quad [2.23]$$

where $V' = \frac{eE}{mv}$

It is sometimes convenient to employ the energy $\varepsilon = \frac{1}{2}mc^2$, (rather than c), as an independent variable, to describe the motion of an electron in a gas. Thus by writing $\varepsilon = \frac{1}{2}mc^2$ and $d\varepsilon = mcdc = (2m\varepsilon)^{\frac{1}{2}} dc$, it could be seen that the population of a shell (c,dc) is proportional to $\varepsilon^{\frac{1}{2}}d\varepsilon$ since $c^2dc - (\frac{2\varepsilon}{m^3})^{\frac{1}{2}} d\varepsilon$. A distribution function $f(\varepsilon)$ is defined such that the point population of the shell (c,dc) is also represented as $(ndr)\varepsilon^{\frac{1}{2}}f_0(\varepsilon)d\varepsilon$, i.e. $4\Pi c^2 f_0(c)dc = \varepsilon^{\frac{1}{2}} f_0(\varepsilon)d\varepsilon$

integrating over all shells gives

$$\int_{0}^{\infty} \varepsilon^{\frac{1}{2}} f_{0}(\varepsilon) d\varepsilon = 4 \Pi \int_{0}^{\infty} c f_{1}(c) dc = 1$$
 [2.24]

In terms of ε , equation (2.23) is equivalent to

$$\left(\frac{\mathrm{m}\varepsilon}{2}\right)^{\mathbf{L}_{2}} \frac{\partial}{\partial t} \left[\mathrm{n}f_{0}(\varepsilon)\right] - \frac{\varepsilon}{3\mathrm{N}q_{m}(\varepsilon)} \operatorname{div}_{\mathbf{r}} \left\{ \mathrm{grad}_{\mathbf{r}}[\mathrm{n}f_{0}(\varepsilon)] + \frac{\partial}{\partial\varepsilon} \left[\mathrm{n}f_{0}(\varepsilon)\mathrm{e}\mathrm{E}\right] \right\}$$

$$- \frac{1}{3} \frac{\partial}{\partial\varepsilon} \left\{ \frac{\varepsilon}{\mathrm{N}q_{m}(\varepsilon)} \operatorname{e}\mathrm{E} \cdot \mathrm{grad}_{\mathbf{r}} \left[\mathrm{n}f_{0}(\varepsilon)\right] \right\}$$

$$+ \left[(\mathrm{e}\mathrm{E})^{2} \frac{\varepsilon}{\mathrm{N}q_{m}(\varepsilon)} + \frac{\mathrm{6m}}{\mathrm{M}} \mathrm{k}\mathrm{T}\varepsilon^{2}\mathrm{N}q_{m_{el}}(\varepsilon) \right] \frac{\partial}{\partial\varepsilon} \left[\mathrm{n}f_{0}(\varepsilon)\right]$$

$$+ \frac{\mathrm{6m}}{\mathrm{M}} \varepsilon^{2}\mathrm{N}q_{m_{el}}(\varepsilon)\mathrm{n}f_{0}(\varepsilon) \right\} - \mathrm{Nn} \frac{\partial}{\partial\varepsilon} \sum_{i} \frac{\mathrm{m}^{2}}{2} \mathrm{I}_{\mathbf{k}}(\varepsilon) = 0 \qquad [2.25]$$

where

$$\frac{m^2}{2} \frac{\partial}{\partial \varepsilon} I_{\mathbf{k}}(\varepsilon) = [(\varepsilon + \varepsilon_{\mathbf{k}_{in}})q_{O_{\mathbf{K}_{in}}}(\varepsilon + \varepsilon_{\mathbf{k}_{in}})f_0(\varepsilon + \varepsilon_{\mathbf{k}_{in}}) - \varepsilon q_{O_{\mathbf{K}_{in}}}(\varepsilon)f_0(\varepsilon)I(\varepsilon - \varepsilon_{\mathbf{k}_{in}})]$$

-
$$[\epsilon q_{O_{K_s}}(\epsilon) f_0(\epsilon) - (\epsilon - \epsilon_{k_{in}}) q_{O_K}(\epsilon - \epsilon_{k_{in}}) I (\epsilon - \epsilon_{k_{in}})]$$

[2.26]

2.4 Expressions for transport coefficients

An expression for the drift velocity may be obtained by considering the whole velocity space to be divided into shells (c,dc) whose radii range in magnitude from zero to infinity. In the presence of an electric field E, a force eE acts on each electron, and a group n dr electrons as a whole moves through the gas. In such circumstances the velocities \underline{c} associated with a shell (c,dc) have, in general, a resultant $\Sigma \underline{c}$ which is not equal to zero. If the total point population of the shell is n_c , then the mean velocity of electrons associated with the shell (c,dc) is

$$W(c) = \frac{\sum_{c} c}{n_{c}}$$

and the mean velocity of all the ndr electrons is

$$W = \frac{\sum_{c} n_{c} W(c)}{n dr}$$

By assuming that the distribution of velocity points within (c,dc) is axially symmetrical about the direction of the mean resultant W(c) of the velocities c of the electrons in the shell and considering the convergent series (equation 2.2) we can see that the population of velocity points n_c of the shell (c,dc) is

$$n_c = (nf_0) (4 \Pi c^2 dc) dr$$
.

The mean velocity W(c) in the direction $\theta = 0$ has a magnitude

$$W(c) = \frac{cf_1}{3f_0}$$

To specify the direction of motion, f_1 is replaced by the vector \underline{f}_1 whose magnitude is $f_1 = f_1(c,r,t)$ and direction is parallel to the axis $\theta = 0$, (i.e. parallel to the force e<u>E</u>). The velocity <u>W</u>(c) is therefore

$$\underline{\mathbb{W}}(c) = \underline{c\underline{f}_1}_{3\underline{f}_0}$$

The magnitudes of f_1 and eE may be related by considering equation 2.6 which can be rewritten as

$$\frac{1}{\nu} \frac{\partial f_1}{\partial t} + \frac{eE}{m\nu} \cdot \frac{\partial f_0}{\partial c} + f_1 = 0$$

In laboratory experiments on diffusing and travelling groups it is now shown that the first term of the above equation is negligibly small in comparison with the second and third terms. Therefore, for a constant electric field we may write

$$\underline{\mathbf{f}}_1 = - \underbrace{\mathbf{eE}}_{\mathbf{m}\mathbf{v}} \frac{\partial \mathbf{f}_0}{\partial \mathbf{c}}$$

and $\underline{W}(c) = \frac{c\underline{f}_1}{3\underline{f}_0} = -\frac{e\underline{E}}{3\underline{m}}\frac{c}{\underline{f}_0}\frac{\partial \underline{f}_0}{\partial c}$.

The drift velocity \underline{W} due to an electric force is the mean value of $\underline{W}(c)$ taken over all shells and is therefore

$$\underline{W} = \underline{4\Pi}{3} \int_{0}^{\infty} \underline{f_{1}} c^{3} dc$$

$$= -\underline{4\Pi}{3} \left(\underbrace{\underline{eE}}{\underline{m}} \right) \int_{0}^{\infty} \frac{c^{3}}{v} \frac{df_{0}}{dc} dc$$

$$= -\underline{4\Pi}{3} \left(\underbrace{\underline{e}}{\underline{m}} \right) \left(\underbrace{\underline{E}}{\underline{N}} \right) \int_{0}^{\infty} \frac{c^{2}}{q_{\underline{m}}(c)} \frac{df_{0}}{dc} dc$$
[2.27]

In terms of energy, the mean of velocities of electrons of the shells with energy range ε to $\varepsilon + d\varepsilon$ is

$$\underline{W} = - \frac{e\underline{E}}{3N} \left(\frac{2}{m}\right)^{\frac{1}{2}} \int_{0}^{\infty} \frac{\varepsilon}{q_{\mathbf{m}}(\varepsilon)} \frac{\mathrm{d}}{\mathrm{d}\varepsilon} f_{0}(\varepsilon) d\varepsilon$$

Before the year 1967 it had been generally assumed that the diffusion of electrons in a gas in the presence of an electric field is isotropic. Under this assumption we proceed to find an expression for the isotropic diffusion coefficient.

Consider equation 2.3. Assume that all collisions are elastic and f_0 is independent of <u>r</u>. Multiply each term by 4Ic^2 and integrate with respect to c from zero to infinity, i.e. over all shells (c,dc). Equation 2.3 is then transformed to

$$\frac{\partial \mathbf{n}}{\partial t} + \operatorname{div}_{\mathbf{r}} \quad \mathbf{n} \left(\frac{4 \mathrm{II}}{3} \int_{\mathbf{0}}^{\infty} c \ \underline{f}_{1} \ c^{2} \ \mathrm{d}c \right) + \left(\sigma_{\mathbf{E}} - \sigma_{\mathbf{coll}} \right) \Big|_{\mathbf{0}}^{\infty} = 0$$

Now, consider equation 2.6. The vector \underline{f}_1 depends on the terms c grad_r(nf₀) and $\underline{eE}_{\overline{m}} \frac{\partial}{\partial c}$ (nf₀) which represent independent processes.

It is shown above (equation 2.22) that

$$n\underline{f}_{1} = - \underbrace{c}_{v} \operatorname{grad}_{r}(nf_{0}) - \underbrace{e\underline{E}}_{mv} \frac{\partial}{\partial c} (nf_{0})$$

Since in the transformed equation above, both the quantities σ_E and σ_{coll} vanish at the limits of integration zero and infinity it follows that the transformed equation, on substituting the value of nf, reduces to

$$\frac{\partial n}{\partial t} \quad \operatorname{div}_{\mathbf{r}} \left[\operatorname{grad}_{\mathbf{r}} \left(4 \operatorname{In}_{3} \int_{0}^{\infty} \frac{c}{v} f_{0} c^{2} dc \right) \right] \quad \operatorname{div}_{\mathbf{r}} \left[\frac{4 \operatorname{II}}{3} \int_{0}^{\infty} \frac{e \operatorname{E} c}{m v} \frac{\partial}{\partial c} (n f_{0}) c^{2} dc \right] = 0$$

The assumption that f_0 is independent of position <u>r</u> implies that W too is independent of <u>r</u>. Since E is constant the transformed equation takes the form

$$\frac{\partial n}{\partial t}$$
 - $D\nabla^2 n$ + \underline{W} . grad_{**r**} (**n**) = 0

where \underline{W} is given by equation 2.27, and the coefficient of lateral diffusion D, is

$$D = 4\Pi \int_{0}^{\infty} \frac{c^{2}}{3\nu} f_{0} c^{2} dc$$

= $\frac{4\Pi}{3N} \int_{0}^{\infty} \frac{c}{q_{m}(c)} f_{0} (c) c^{2} dc$ [2.28]

In terms of energy

$$D = \frac{1}{3N} \left(\frac{2}{m}\right)^{\frac{1}{2}} \int_{0}^{\infty} \frac{\varepsilon}{q_{m}(\varepsilon)} f_{0}(\varepsilon) d\varepsilon .$$

The expressions obtained above (equations 2.28) are for the lateral diffusion coefficient. They are based on the assumption that in the presence of an electric force diffusion of electrons is isotropic. This assumption has been challenged in 1967 by the experimental discovery of Wagner, Davis and Hurst that diffusion is, in general, anisotropic. Thus, it is now recognised that there are two diffusion coefficients, i.e. lateral and longitudinal diffusion coefficients respectively denoted in the present work by D and D_L (see section 2.3.2; see also Huxley and Crompton 74, for complete theoretical discussion on D_L).

One parameter which has proved convenient in studies of the motion of electrons in gases is that termed the characteristic energy ε_k (Frost and Phelps 1962). The characteristic energy is defined as:

 $\varepsilon_{\mathbf{k}} = \underline{eD}_{\mu}$ where μ is the mobility of electrons $\begin{pmatrix} \mu = \underline{W} \\ \underline{E} \end{pmatrix}$.

It follows from equations 2.27 and 2.28 that

$$\varepsilon_{\mathbf{k}} = \underline{eD}_{\mu} = - \int_{0}^{\omega} [\varepsilon/q_{\mathbf{m}}(\varepsilon)] f_{0}(\varepsilon) d\varepsilon \qquad [2.29]$$

where $q_m(\varepsilon)$ is the effective momentum transfer cross section.

2.5 Boltzmann Holstein Equation

The working scalar equation (equation 2.25) can be simplified by assuming that the total inelastic cross section is small compared with the elastic cross section. With this assumption and the omission of the time and spatial dependence terms, equation (2.25) becomes

$$\frac{d}{d\varepsilon} \left\{ \begin{bmatrix} (eE)^2 & \frac{\varepsilon}{Nq_m(\varepsilon)} + \frac{6m}{M} kT \varepsilon^2 Nq_m(\varepsilon) \end{bmatrix} \frac{dt}{d\varepsilon} + \frac{6m}{M} \varepsilon^2 Nq_m(\varepsilon) f(\varepsilon) + 3N \sum_{\mathbf{ik}} \frac{m}{2} I_{\mathbf{ik}} \end{bmatrix} = 0$$
[2.30]

where
$$I_{\mathbf{ik}} = \frac{2}{m^2} \int_{\varepsilon}^{\varepsilon + \varepsilon_{\mathbf{ik}}} \left[f(y) - f(y - \varepsilon_{\mathbf{ik}}) \exp\left(-\frac{\varepsilon_{\mathbf{ik}}}{kT}\right) \right] q_{\mathbf{o}_{\mathbf{ik}}}(y) y \, dy$$
, [2.31]

in which $q_{o_{ik}}$ is the cross section for the kth transition of the ith inelastic process and ε_{ik} is the threshold for this transition.

Equation (2.30) is equivalent to the form of Boltzmann equation developed by Holstein (1946) and Margenaus (1946). However, the extension of the equation to include superelastic collisions has been made by Frost and Phelps (1962). A solution proposed by these authors is obtained by integrating equation (2.30) once to give

$$\left[(eE)^{2} \frac{\varepsilon}{Nq_{m}(\varepsilon)} + \frac{6m}{M} kT\varepsilon^{2}Nq_{m}(\varepsilon) \right] \frac{df}{d\varepsilon} + \frac{6m}{M} \varepsilon^{2}Nq_{m}(\varepsilon)f(\varepsilon)$$
$$+ 3N \sum_{ik} \frac{m^{2}}{2} I_{ik} = 0 \qquad [2.32]$$

If a normalised variable of the form ε/kT is employed (note) that this transformation requires another transformation z'=Y/kT in the expression for I_{ik} equation 2.31), then, dividing throughout by N(kT)²q_o^{6m}/M, where q_o is the value of q_m at some reference energy, the following is obtained.

$$\left\{\frac{M}{6m} \frac{(eE)^2}{N^2 q_0 q_m(Z) (kT)^2} + Z\left[\frac{q_m(Z)}{q_0}\right]\right\} Z \frac{df}{dZ} + Z^2 \frac{q_m(Z)}{q_0} f(Z)$$

$$+ \sum_{i} \frac{M}{2m} \int_{z}^{z+z_{ik}} \left[f(Z') - f(Z'-Z_{ik}) \exp -Z_{ik}\right] \frac{q_{0ik}(Z')}{q_0} Z' dZ' = 0$$
[2.33]

On introducing the additional normalised variables

$$\theta = \frac{q_m(Z)}{q_o}$$
 and $\eta_{1k} = \frac{Mq_{o_{ik}}(Z)}{2mq_o}$ and the constant

(for a given set of experimental conditions)

$$\alpha = \left(\frac{M}{6m}\right) \left(\frac{eE}{Nq_{o}kT}\right)^{2}$$

equation (2.33) becomes

$$\begin{pmatrix} \alpha + \theta Z \\ \theta \end{pmatrix}^{Z} \frac{df}{dZ} + Z^{2} \theta f + \sum_{z} \int_{z}^{z+z_{1k}} \left[f(Z') - f(Z'-Z_{1k}) \exp -Z_{1k} \right] \eta_{1k}(Z') Z' dZ' = 0$$

$$[2.34]$$

Equation 2.34 is referred to as Boltzmann Holstein equation which can be simplified further when collisions of the second kind are neglected. In this case it becomes

$$\left(\frac{\alpha}{\theta} + \theta Z\right)^{Z} \frac{df}{dZ} + Z^{2}\theta f + \sum_{ik} \int_{z}^{z+z_{ik}} f(Z') \eta_{ik} (Z') Z' dZ' = 0 \qquad [2.35]$$

2.6 <u>Modification of Boltzmann-Holstein Equation for a Multicomponent</u> <u>Gas</u>

The theoretical discussion presented in the preceding sections follows the terminology and formulation of Huxley and Crompton (1974) and none of it is original. This reference covers the theoretical aspects of the subject in great detail and hence for a complete discussion the reader is referred to it.

One important area which seems to be theoretically rather neglected is the behaviour of electrons in a multicomponent gas. The transport coefficients of electrons through a gas have been found to depend critically on the presence of small amounts of impurities or additives. The effect is a strong function of the nature of the additive as well as the nature of the contaminated gas. In the special case of rare gases the effect is very pronounced since it strongly moderates the electron energy and affects the electron energy distribution. The change in drift velocity W and characteristic energy $\varepsilon_{\mathbf{k}}$ (= eD/µ), when a molecular gas is added in small proportions to an inert gas has been exploited as a means of deriving information about collision cross sections.

Engelhardt and Phelps (1964) have calculated the drift velocity W, the magnetic drift velocity W_M and the characteristic energy $\varepsilon_{\mathbf{k}}$ for mixtures of H₂ and Ar in order to check the validity of previously derived momentum transfer and inelastic cross sections for both gases. These authors have made use of the fact that Ar has no inelastic processes below 11.5 eV to scrutinise the inelastic processes of rotation and vibrational excitation in H₂ at low $\varepsilon_{\mathbf{k}}$ values. Their calculations are based upon evaluating W and $\varepsilon_{\mathbf{k}}$ for a mixture using the collision cross sections and the mixture composition as their variables. For convenience they have used the energy exchange collision frequency, ν/N , defined by the relation,

$$\nu/N = \left(\frac{eWE}{N}\right) / (\varepsilon_k - kT)$$

From this relation, ν/N values have been calculated for the constituent components of a mixture, by substituting the appropriate W and $\varepsilon_{\mathbf{k}}$ experimental data. Then, the energy exchange collision frequency for the mixture could be calculated from the relation,

$$\frac{1}{F} \begin{bmatrix} \underline{\nu} \\ N \end{bmatrix}_{Mix} = \begin{bmatrix} \underline{\nu} \\ N \end{bmatrix}_{H_2} + \frac{1-F}{F} \begin{bmatrix} \underline{\nu} \\ N \end{bmatrix}_{Ar},$$

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where F, is the fraction of hydrogen in the mixture. Using the two relations above, Engelhardt and Phelps have calculated ε_k and W in a range (1.0% to 10%) H₂ in Ar mixtures. They found that there were several regions in disagreement with W and ε_k experimental values. The maximum discrepancy between calculated and measured values of these parameters ranged from 10% to 20%. They remarked that the presence of this discrepancy in the pure argon data for ε_k near 1.0 eV, suggested that they had not used the 'optimum' momentum transfer curve for argon at energies below 1.0 eV.

The argon momentum transfer cross-section, q_{mA} , has been subject to a large number of investigations. The values derived by Frost and Phelps (1964), O'malley (1963), Bowe (1960) and Barbieri (1951) are in satisfactory agreement. The small discrepancies between the results of these authors do not fully justify the disagreement between the calculated and measured transport coefficients in argon-hydrogen mixtures found by Engelhardt and Phelps. It should be noted, however, that the momentum transfer cross-section for argon which has been derived fairly recently by Milloy <u>et al</u>. (1977) differs considerably, at the low energy range (below 0.5 eV), from that of Frost and Phelps (1964). This may justify the remark of Engelhardt and Phelps mentioned above. Nevertheless, for reasons that will become apparent subsequently, the method of calculation of these authors is believed to be partly responsible for the disagreement between their calculated transport coefficient and the observed data.

Palladino and Sadoulet (1975), have applied a method similar to that of Engelhardt and Phelps, for computing the drift velocity and magnetic drift velocity W_M for a range of mixtures of isobutane in argon and methane in argon. In some parts of their velocity curves

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Fig. 2.2 Calculations of W and W_m for different concentrations of argon isobutane mixture (Palladino and Sadoulet 1975) compared with measurements of Charpak (1973).



Fig. 2.3 Comparison between calculated and measured results for A/10% CH₄ (Palladino and Sadoulet 1975).

(fig. 2.2), the discrepancy between their calculated W and W_M values and measurements of Charpack <u>et al</u>. (1973) for argon-isobutane mixtures is as large as 40%. For 90% Ar - 10% methane the calculated W is about 25% greater than the measured value in the peak region and about 20% smaller in the saturation region (fig. 2.3). It is likely that these discrepancies have arisen mainly from the method of calculation. This method which employs the collision cross-sections and the proportions of the constituent components of the mixture as variables, is believed to be inadequate to calculate the transport coefficients.

Another method which has been used by Christophorou and Christodoulides (1969) employs an expression of the form

$$W_{\text{Mix}}^{-1}\left(\frac{E}{P}\right) = W_{\text{E}}^{-1}\left(\frac{E}{P}\right) + S\left(\frac{E}{P}\right)\frac{P_{1}}{P_{\text{E}}}$$

in which W_{Mix} is the drift velocity for a mixture of a polar gas in ethylene, $S\left(\frac{E}{P}\right)$ is the slope of $W(^{E}/P)$ curves and $\frac{P_1}{P_E}$ is the ratio of the partial pressures of the impurity to that of ethylene. The expression has been used to compare calculated drift velocities, for mixtures of polar gases in ethylene, with the measured values as a function of partial pressures.

This method is oversimplified because it may give satisfactory agreement only in the low E/p region where W varies approximately linearly with E/p.

It is desirable therefore, to develop a method of calculation of transport coefficients for gas mixtures that employs the same theory as for a single component gas. Very recently, Schultz and Gresser (1978) have given results of calculations of drift velocity in various counting gas mixtures. The work of these authors extended the previous study of Palladino and Sadoulet (1975). During the course of this

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work, detailed calculations of electron transport coefficients in a range of gas mixtures were also made. Although the basic physics of the two approaches is the same, the details appear to differ considerably. The two areas in which the two treatments appear to diverge are in the adaptation of the theory to multi-component gases and in the calculation of inelastic scattering effects. Since some of the gases studied by Schultz and Gresser are covered in the present work it will be of considerable interest to compare the results of the two approaches to the calculations of transport coefficients. (The results of Schultz and Gresser will be discussed in detail in chapter 7.)

Adaptation of the theory for a single-component gas, discussed in the preceding sections, to multi-component gas mixtures may be accomplished by considering, during the argument which establishes the Boltzmann-Holstein equation, the total collision frequencies. That is, a summation of collision frequencies must be made over all the gas components present.

The total flux $\sigma_{coll}(c)$ becomes, in place of equation 2.7,

$$\sigma_{\text{coll}}(c) = \sum_{i} 4 \Pi n_{o} c^{2} \nu_{iel} \left(\frac{m}{M_{i}} cf_{0} + \frac{\overline{C^{2}}}{3} \frac{df_{0}}{dc} \right)$$
$$= 4 \Pi n_{o} c^{2} \left(mcf_{0} \sum_{i} \frac{\nu_{iel}}{M_{i}} + \frac{\overline{C^{2}}}{3} \frac{df_{0}}{dc} \sum_{i} \nu_{iel} \right)$$
[3.36]

where v_{iel} is the collision frequency for elastic collisions with the ith gas component having molecular mass M_i.

In the vector equation, (equation [2.14']), the quantity \underline{V}' becomes

$$\underline{\mathbf{V}}' = \underline{\mathbf{eE}}_{\mathbf{m}} \frac{1}{\sum_{\mathbf{v}_{\mathbf{i}}} \mathbf{v}_{\mathbf{i}}}$$

where v_i is the effective collision frequency of the ith component.

$$v_{\mathbf{i}} = v_{\mathbf{i}_{el}} + v_{\mathbf{i}_{O_{in}}} I(c - c_{\mathbf{i}_{in}})$$

For each type of collision frequency, v = c(p/kT)q, where q is the appropriate cross-section and p is the partial pressure of the particular gas component.

If now the arguments leading to equation (2.35) are again carried through we find that they lead to the following modified equation:

$$\left(\frac{\alpha}{\theta'} + Z\theta\right)^{\mathbb{Z}} \frac{\mathrm{df}}{\mathrm{dZ}} + Z^{2}\theta f + \sum_{\mathbf{ik}} \int_{\mathbf{z}}^{\mathbf{z}+\mathbf{z}_{\mathbf{ik}}} f(Z') \eta_{\mathbf{ik}} (Z') Z' \mathrm{dZ}' = 0 \qquad [2.37]$$

where

$$\theta = \sum_{i} f_{i} \frac{q_{i}/q_{o}}{M_{i}/M_{o}} , \qquad \theta' = \sum_{i} f_{i} \frac{q_{i}}{q_{o}}$$
$$\eta_{ik} = \frac{M_{o}}{2m} f_{i} \frac{q_{ik}}{q_{o}} \qquad \text{and} \qquad \alpha = \left(\frac{E}{P}\right)^{2} \frac{M_{o}e^{2}}{6mq_{o}^{2}}$$

In these expressions q_i is the elastic cross-section for the ith component, q_{ik} is the inelastic cross-section for the kth level of the ith component, Z_{ik} is the threshold energy (normalised to kT) for the kth level and f_i is the fraction of the total pressure due to the ith component. The quantities M_0 and q_0 are convenient normalising numerical constants, taken in the present work as the hydrogen atomic mass and 10^{-15} cm² respectively.

Having obtained the energy distribution f(Z), the transport coefficients may be calculated, numerically, from the following integrals:*

^{*} It is convenient in the present work on gas mixtures to consider system pressure p = NkT rather than the number density N.

$$W = -\frac{2}{3} \left(\frac{eE}{m}\right) \int_{0}^{\infty} \frac{\varepsilon^{3/2}}{\Sigma v} \frac{df(\varepsilon)}{d\varepsilon} d\varepsilon$$

$$= -\frac{2}{3} \left(\frac{E}{p}\right) \frac{e}{q_{o}} \left(\frac{kT}{2m}\right)^{\frac{1}{2}} \int_{0}^{\infty} \frac{Z}{\theta'} \frac{df(Z)}{dZ} dZ$$

$$D = \frac{2}{3m} \int_{0}^{\infty} \frac{\varepsilon^{3/2}}{\Sigma v} f(\varepsilon) d\varepsilon$$

$$\frac{1}{3p} \left(\frac{2}{m}\right)^{\frac{1}{2}} \frac{(kT)}{q_{o}}^{\frac{3/2}{2}} \int_{0}^{\infty} \frac{Z}{\theta'} f(Z) dZ$$

$$[2.39]$$

The characteristic energy $\varepsilon_{\mathbf{k}}$ is defined as $\frac{eD}{\mu}$ where μ is the electron mobility W/E. Thus $\varepsilon_{\mathbf{k}}$ may be found using equations 2.38 and 2.39 above. The mean electron energy $\bar{\varepsilon}$ is given by

$$\overline{\varepsilon} = kT \int_{0}^{\infty} Z^{\frac{3}{2}} f(Z) dZ$$

In the derivation of equation 2.33, which leads to the modified Boltzmann-Holstein equation (eqn. 2.37), it may be shown that the asymmetry coefficient $f_1(Z) = (kT)^{\frac{3}{2}} f_1(\varepsilon)$ is given by

$$f_1(Z) = -\left(\frac{E}{P}\right)\frac{e}{q_o}\frac{1}{\theta'}\frac{df_0}{dZ}$$

Thus the mean value of the ratio f_1/f_0 , which may be referred to as the asymmetry ratio, is given by

$$\left\langle \frac{f_1}{f_0} \right\rangle = -\left(\frac{E}{P}\right) \frac{e}{q_0} \int_0^\infty \frac{Z^{\frac{1}{2}}}{\theta'} \frac{df_0}{dZ} dZ \qquad [2.40]$$

The distribution must, of course, be normalised. That is

$$\int_{0}^{\infty} Z^{2} f(Z) dZ = 1$$

Equations (2.38), (2.39) and (2.40) have been employed, with the modified definition of θ' , for calculation for gas mixtures of the drift velocity W, the lateral diffusion coefficient D and the asymmetry ratio $\langle f_1/f_0 \rangle$.

2.7 Solution of the Modified Equation

During the course of derivation of the various equations that have led to equation 2.37 several assumptions are made. In summary these assumptions are:

(1) Collision of the second kind are neglected. Justification of this assumption depends on two factors; (a) the smallest threshold energy ε_{in} for inelastic encounters, and (b) the number density N_o, of molecules in the ground state.

The number of molecules in the state with threshold energy ε_{in} is

$$N_o \exp (-\epsilon_{in}/kT)$$

In some molecular gases ε_{in} are comparable in magnitude with kT at room temperatures and the number of molecules in rotational states other than the ground state is an appreciable proportion of the whole. In such an event this assumption is not justified. Collisions of the second kind have not been included in the present calculations since at or near room temperature the excited vibrational levels of the gases considered have essentially zero population. Further, since the excitation energies are small compared with the average electron energy, and small compared with the vibrational excitation energies, the net effect on the distribution function is negligible.

(2) The velocity distribution function may be expressed by the series(equation 2.2),

$$f(c,\theta,r,t) = f_0(c,\theta,r,t) + \sum_{k=1}^{\infty} f_k(c,r,t) P_k (\cos \theta)$$

The justification for ignoring the higher order harmonics is that $f_1 \ll f_0$. This is an excellent approximation when no inelastic scattering is present, e.g. argon at normal E/N values, but some calculations carried out during the course of this work suggest that there may be situations in which this assumption is invalid. Nevertheless, the computational time and effort required in considering the higher harmonics is excessive and would not, it seems alter the calculated transport parameters seriously, (further detail in chapter 7). (3) It is assumed that the inelastic scattering is isotropic. This assumption requires that q_{el} to be much greater than q_{in} over a useful range of speeds c, in which event the second term on the right-hand side of equation 2.14 can be omitted on the grounds that it is much smaller than the first term. This assumption is not true, in general, and certainly not valid in hydrocarbon gases where q_{el} is comparable with qin. Introduction of this assumption serves in simplifying the general transport equation.

(4) It is assumed that the velocity distribution is spatially independent. This assumption is not true for some hydrocarbons, e.g. methane (Duncan and Walker 1972). Bowman and Gordon (1967) show, however, that for a system similar to that used in this work corrections to W and D/μ are insignificant.

Under these assumptions equation 2.37 is solved in the following manner:

Let f(Z) be represented by

$$f(Z) = A \exp \left[-\int_{0}^{Z} G(Z') dZ'\right]$$
 [2.41]

where A is determined by the normalisation condition $\int_{0}^{\infty} Z^{\frac{1}{2}} f(Z) dZ = 1$. Then $\frac{df}{d7} = -f G(Z)$ [2.42]

Putting (2.41) and (2.42) into equation 2.37 and re-arranging we get:

$$G(Z) = \frac{1}{1 + \frac{Z^2 \theta f(Z)}{Z \theta' \theta}} \sum_{z} \int_{z}^{z+z_{ik}} \int_{z} f(Z') \eta_{ik} Z' dZ'} [2.43]$$

with all the notations as before. In this expression, for simplicity of notation, the summation and integral (inelastic scattering term) in equation (2.43) may be replaced by S(Z,f). We may, then, write

$$G(Z) = \frac{1 + S(Z,f)/Z^{2}\theta f}{1 + \alpha/Z\theta\theta'}$$
 [2.44]

For the present work the modified Boltzmann-Holstein equation has been solved numerically by a self-consistent, iterative method of the type first used by Locus (1969). An initial, trial distribution f(Z)is employed to compute S(Z,f) and hence to find the function G(Z) from equation [2.44]. This function is then used, in equation [2.41], to calculate a new distribution f(Z), and so on. Iteration proceeds until f remains stable. In the present calculations an upper energy limit ε_L was chosen (normally a few eV) and, for the purpose of integration and to define the functions f, S and G, this energy range was divided into 2^n equal intervals with n increasing by unit steps from 7 to 11. At each value of n, iteration was allowed to proceed until the mean energy $\overline{\varepsilon}$ had stabilised to within 0.05%. Depending upon the particular situation the number of iterations required at n = 7 varied between 7 and 32. At each increase in n, twice as many values are

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required to define the new trial function f. These new values were simply found by linear interpolation between the f values for the previous n. A Maxwellian distribution was chosen for the initial trial function, for n = 7, but it was established that the final function was quite independent of the initial choice. The change in calculated values for W, D, $\langle f_1/f_0 \rangle$ and $\bar{\epsilon}$ between n = 10 and n = 11 was always acceptably small, less than 0.2% for W and D and less than 0.1% for $\langle f_1/f_0 \rangle$ and $\bar{\epsilon}$.

The function S(Z,f) was evaluated in practice from the expression

$$S(\mathbf{Z},\mathbf{f}) = \sum_{\mathbf{k},\mathbf{i}} \sum_{\mathbf{z}} \int_{\mathbf{z}}^{\mathbf{z}_{L}} \mathbf{f}(\mathbf{Z}') \mathbf{Z}' \eta_{\mathbf{i}\mathbf{k}}(\mathbf{Z}') d\mathbf{Z}' - \sum_{\mathbf{k},\mathbf{i}} \sum_{\mathbf{z}} \int_{\mathbf{z}+\mathbf{z}_{\mathbf{i}\mathbf{k}}}^{\mathbf{z}_{L}} \mathbf{f}(\mathbf{Z}') \mathbf{Z}' \eta_{\mathbf{i}\mathbf{k}}(\mathbf{Z}') d\mathbf{Z}' ,$$

where $Z_L = \varepsilon_L/kT$. At each value of E/p it was established that the calculated results were independent of the choice of upper energy limit ε_L .

The calculations were carried out by a Cyber 72 computer. The program used, is presented in Appendix I.

CHAPTER 3

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CRITICISMS OF PREVIOUS MEASUREMENTS OF TRANSPORT COEFFICIENTS

3.1 Introduction

In chapter 1 the principle concepts of the methods that have been used to measure the transport coefficients of electrons in gases were reviewed. These methods are, the Townsend method, the electrical shutter method and the pulse method for measuring drift velocity, and the Townsend method for measuring the longitudinal diffusion coefficient. Also discussed briefly in chapter 1 were some of the limitations of these methods and the possible reasons for some of the disturbing discrepancies in transport coefficients data that exist in the literature. Three main reasons are believed to be responsible for these discrepancies. Firstly, there are instrumental factors that limit the accuracy of measurement. The principle factors are (a) timing inaccuracies resulting from various reasons such as inexact definition of electron paths, systematic and calibration inaccuracies and inaccuracies inherent in some of the modes of timing (e.g. timing from oscilloscope readings), and (b) electric field distortion especially in the vicinity of the boundary of the electron (or electron group) flight path. The second main reason for discrepancies concerns the impurity of gases and the inaccuracies in proportions of the constituent components in multi-component gases. Thirdly, improper data analysis may be responsible for errors in some cases.

In this chapter the limitations of previous experimental work in the field will be examined and analysed in more detail. It will be shown in later chapters how some of these limitations have been overcome in the present investigations and how attempts have been made to improve the accuracy of measurement.

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3.2 Drift velocity measurement

Among the basic methods, discussed in chapter 1, that have been used for measuring drift velocities of electrons in gases, those which are based on measuring the time-of-flight seem, in principle, the most simple and straightforward. Under the time-of-flight category one may include two of the three principle methods mentioned above, i.e. the electrical shutter method and the pulse method. The third principle method, i.e. the Townsend method, for measuring electron drift velocity is not as simple from the data analysis viewpoint because it measures the magnetic drift velocity W_M rather than W. The disadvantages of this method have been outlined in section 1.2.1 and will not be discussed further.

3.2.1 The electric shutter method

The original interpretation of time-of-flight experiments based on the use of electrical shutters was extremely simple. The first shutter was seen as a gate which admitted a well defined electron group into the drift space at a known time, while it was supposed that the second shutter could be used to sample the time variation of the electron density at a plane a known distance h from the first shutter without disturbing the number density at any time. With these assumptions, the transit time of the group was taken as the time interval between the opening of the shutters that corresponded to maximum transmission of the second shutter. The drift velocity was then generally determined from W= h f, where f is the frequency with which the shutters opened. The assumption that the time required for the centre of an undisturbed pulse to travel the distance h is 1/f, is not exactly true for the following reasons:

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(i) Some electrons from each pulse will be absorbed owing to back diffusion by the first shutter after it is shut. This slightly alters the position of the maximum of the electron density for the pulse from that corresponding to the ideal case of an undisturbed group.

(ii) The pulse is disturbed by the absorption of electrons by the second shutter before it opens.

(iii) The shutters transmit electrons of high speed more readily than electrons of low speed. Thus error will be introduced due to any variation of the mean agitational speed \bar{c} of the electrons along the length of the pulse.

(iv) The frequency corresponding to maximum electron current is not equal to the frequency corresponding to maximum electron density of the undisturbed pulse at the second shutter because of diffusion current.

(v) The number of electrons in each pulse varies as the frequency is varied.

(vi) Current/frequency curves will not be symmetrical about each current maximum because there is continuous decay of the maximum electron density of a pulse while it is passing through the second shutter.

The effect of the factors (i), (ii) and (iii) was analysed by Lowke (1962) while the effect of the factors (iv), (v) and (vi) was analysed by Duncan (1957). The individual contributions to the total error in an electrical shutter experiment, as applied to the case of a plane source of electrons, are summarised in the following:

(i) The relative error due to back diffusion is given by $\frac{2}{h} \left(\frac{W}{D} \right)$ [Lowke (1962)].

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(ii) The relative error due to the influence of the boundary condition imposed by the second shutter is $\frac{1}{h} \left(\frac{W}{D} \right)$ [Lowke (1962)].

(iii) The varying value of \bar{c} within the pulse introduces an error, the value of which is unknown [Lowke (1962)].

(iv) The relative error due to diffusion is $\frac{1}{h} \left(\frac{W}{D} \right)$ [Duncan (1957)].

(v) The varying number of electrons in each pulse with change in frequency changes the relative error by $-\frac{2}{h}\left(\frac{W}{D}\right)$ [Duncan (1957)].

(v) The relative error due to the decay with time of each pulse is $\frac{1}{h} \left(\frac{W}{D} \right)$ [Duncan (1957)].

The total relative error is obtained by adding the above individual contributions.

Despite the inherent simplicity of the electrical shutter method there seems to have been some reluctance to use it because of reservations about the end effects caused by the distortion of the electric field in the vicinity of the shutters. In order to overcome these end effects, Phelps <u>et al</u>. (1960) used a technique in which two different drift distances were employed, the drift velocity being calculated from the ratio of the difference between the drift distances to the difference between the transit time (see section 1.2.2). From the discussion above on the factors contributing to the total error, it is not difficult to see that this differencing technique also eliminates, to a first approximation, errors from diffusion.

Although the differencing technique in the electrical shutter method appears in principle to be capable of giving accurate drift velocity results, Phelps <u>et al</u>. found some evidence of end effects at low E/p values. Their results at low E/p were found to depend on the drift distance, differences of 10% to 20% being obtained between the results recorded using drift distances of 2.54 and 6.35 cm. Phelps

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et al. have suggested that this sort of variation could not be ascribed to contact p.d. They assumed that some unknown end effect caused the effective drift distance to depend slightly on the experimental conditions. One possible explanation for the variation is that it may have been caused by the somewhat wide spacing of the shutter wires (1.0 mm) (Huxley and Crompton 1974). The wide spacing would have increased the transmission to the second shutter when the first was quiescent, but would also have led to increased field distortion in the vicinity of the shutters. Except possibly at low E/p values the differencing technique provides, in principle, a reliable method for eliminating end effects. It must, however, be applied with care in order to achieve a high degree of accuracy. In drift velocity measurement the parameters required are the drift distance x and the drift time t of an electron (or electron group). With the differencing technique, if Δt is the interval between two absolute times t_1 and t_2 corresponding to drift distances x_1 and x_2 , then small errors in t_1 , t_2 , x_1 and x_2 can, clearly, lead to relatively large errors in the drift velocity values. Furthermore, with the differencing technique it will be advantageous to carry out W measurement by employing a range of drift distances rather than just two. This will enable W to be determined from a set of results instead of just one $\frac{\Delta x}{\Delta t}$ ratio. Using a larger range of drift distances will, also, help in investigating any dependence of W on the drift distance as suggested by Phelps et al. when using the differencing technique.

3.2.2 The Pulse method

The second principle method for measuring W that can be classified as a time-of-flight method is that which depends on measurement of

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arrival time distribution (termed in the present work as the pulse method - see section 1.2.3). A novel pulse technique which appears in principle to be capable of measuring both drift velocities and diffusion coefficients simultaneously was initiated by the ORNL group in the early 1960's. The experimental apparatus and method for measuring W by this technique have been described in section 1.2.3.

Consider equation 1.3 for E(t). This equation which has been used by Hurst et al. (1963) to derive the transport coefficients from the arrival time spectrum is based on three assumptions. Firstly, it assumes that the initial electron distribution at the cathode can be approximated by a delta function; secondly, that the effect of instrumental electronic noise on the distribution is negligible; and thirdly, that no distortion in the arrival time distribution results from the dead-time of the detection system. In practice the effect of the finite width of the UV pulse and electronic noise is to broaden the distribution. The effect of the dead-time of the detection system, on the other hand, is to displace as well as to broaden the distribution. This shift of the arrival time distribution, which is termed by the ORNL group as "Poisson distortion", clearly affects the accuracy of the drift velocity measurement. Hurst and Parks (1966), and Wagner, Davis and Hurst (1967) have accounted for the effect of Poisson distortion analytically in the following manner; the analyzer output records E(t) accurately, provided that every electron entering the detection system from every pulse is recorded. The dead-time of the detector or analyzer is usually long compared with the width of the arrival time distribution, so that if two or more electrons enter the detector from a significant number of pulses, electrons later in the pulse are discriminated against, since they fail to be recorded. In

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Fig. 3.1 Calculated curves illustrating the effect of Poisson distortion for various values of \bar{n}_c (from Hurst and Parks 1966).



Fig. 3.2 Correction factor for W due to Poisson distortion and the use of equation $W = d/t_m$; C/F is the number of electrons counted per light flash (from Wagner, Davis and Hurst 1967).

such an event the spectrum will be biased towards electrons in the leading part of the pulse and therefore ignoring this discrimination will lead to measured values of W which are too large. The condition to be satisfied for single electron detection is $\bar{n}_c \ll 1$, where \bar{n}_c is the average number of electrons entering the detector per pulse. Fig. 3.1 shows calculated spectra for various values of \bar{n}_c (Wagner, Davis and Hurst - 1967). These authors have also calculated the correction factor for W as a function of two experimentally obtainable ratios, $\ensuremath{^{C/F}}$ and The former quantity represents the total number of counts C <u>ðt</u> 2tm• recorded from F pulses. The ratio C/F is related to \bar{n}_c such that $C/F \rightarrow \bar{n}_c$ as $\bar{n}_c \rightarrow 0$. The ratio $\delta t/2t_m$ is defined as before (section 1.3.2); $\delta t = |t_1 - t_m|$, t_1 is the value of t such that $E(t_1) = E(t_m)/e$ and t_m is the time at which maximum E(t) is recorded. Fig. 3.2 shows the correction factor, calculated by Wagner et al., that accounts for the combined effects of the decay of the group and Poisson distortion.

3.3 Diffusion Coefficients Measurements

Almost all research on electron diffusion in gases, up to the early 1960's, has been based on the original method which measures D/W, set forth by Townsend in the early years of this century. However, a new experimental approach has been taken by the ORNL group (Hurst <u>et</u> <u>al</u>. 1963) to measure the diffusion coefficient.* In section 1.3 the experimental methods of both techniques have been described. In this section the limitations of both techniques will be discussed.

^{*} It is now recognised that the quantity measured by the ORNL group was the longitudinal diffusion coefficient D_L rather than the isotropic diffusion D.

3.3.1 The Townsend method

This method for measuring diffusion coefficients is a well established technique. It has been in use over the last seventy years. The technique has been subject to continuous development and constant improvement to increase the precision of measurement. Although there have been significant variations in the application of the Townsend technique over the years, its essence remains unchanged. The principle of the method, which is based on the assumption that the diffusion of electrons in the presence of a uniform and constant field is isotropic, is very simple. However, interpretation of the experiments is less straightforward and has been the subject of considerable controversy. Doubts have sometimes been expressed about the validity of the results derived from Townsend lateral diffusion method because of the influence of the boundaries on the distribution of electron number density within the diffusion chamber, and the (sometimes) poor agreement between the results from different experimental groups. The doubts about the former factor are unjustified because it has been shown (Huxley and Crompton 1974) that, for the experimental conditions that have been used for the majority of the measurements, the results are scarcely affected by phenomena that occur near the electrodes. As for the latter factor, recent years have seen marked improvement in the accuracy of measurements. This has come about as a result of the increasing understanding of the factors that degrade that accuracy. Among these factors, the discovery of the anisotropic nature of diffusion, (Wagner, Davis and Hurst 1967), the observed dependence of the measurements on experimental parameters, notably the geometry of the diffusion apparatus and the number density of the gas (Lowke 1962), and (Crompton and Jory 1962). These results initiated a series of theoretical

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investigations mainly by members of the Electron and Ion Diffusion Unit at The Australian National University. For example, Crompton (1969) studied the contribution of swarm techniques to the solution of some problems in low energy electron physics as applied to both the Townsend method for lateral diffusion and the time-of-flight method for longitudinal diffusion.

As discussed in section 1.3.1 application of the Townsend method to determine the lateral diffusion coefficient requires measuring the ratio R of the current collected on a central disc to the total current received on a plane electrode. The factors influencing the accuracy of this method have been thoroughly investigated by Crompton, Elford and Gascoigne (1965). One of the main factors that govern the accuracy of measurement is the choice of the dimensions a, b, and h, and the width of the annular gap separating the central disc and the surrounding annulus of the receiving electrode. As well as these geometrical parameters, another factor related to the construction of the apparatus is of equal importance, namely, the uniformity of the electric field within the diffusion chamber. Field distortion can occur as a result of two main factors:-

(i) It can be introduced by incorrect geometry of the guard electrode structure or of the source electrode, or the collecting electrode not being a true geometrical plane.

(ii) It can be produced by contact potential differences, either over a surface or between different surfaces.

A third factor that plays an important rôle in the accuracy of lateral diffusion measurement is the current ratio measuring device. In order to avoid the effects of space charge repulsion in electron swarms it is necessary to ensure that the electron number density is

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Fig. 3.3 Schematic diagram of induction balances for measurement of current ratios.

very low. It may be necessary, therefore, for the current arriving at the receiving electrode to be as small as 10^{-13} A.

Measurement of the current ratios in almost all recent lateral diffusion experiments has been determined by systems developed from the method originated by Townsend (1914). A modern version used by Crompton <u>et al</u>. (1965) is shown in fig. 3.3. In their method these authors employed a pair of induction balances. A ramp generator connected to points A and B produced an accurate linear sweep voltage which was applied to the capacitor C_1 . A known fraction of the voltage was applied to a second capacitor C_2 by means of the potentiometer P. With this arrangement two constant displacement currents i_1 and i_2 were generated, the ratio of which was determined simply by the setting of P.

Full advantage could be taken of the method only by making it an integrating one, with the integration commencing when $V_1 = V_2 = 0$ and terminating just before the ramp voltage reached its maximum value. To effect this a correctly phased signal operated the electromagnetic earthing switches S. The switches were designed to inject minimum charge into the electrometer circuits on opening as a result of contact potential differences between the moving contacts. The potentials of the electrodes R_1 and R_2 were monitored with the electrometers E.

Such systems have been proved to give satisfactory performance particularly when used to measure relatively large currents ($\sim 10^{-12}$ A). Currents of this order may introduce space charge effect which degrades the accuracy of the diffusion measurement. It is desirable, therefore, to employ a system which is more sensitive and capable of measuring currents down to 10^{-14} A. The availability now of high performance phase-sensitive detectors and of low noise operational amplifiers

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allows the construction of a system which is simpler and relatively less costly than the integrating induction balance. Such a system for measuring the ratio of very small currents is described in detail in section 4.4.

3.3.2 Longitudinal diffusion measurement

The search for alternative methods to measure diffusion coefficients has led to the discovery of anistropic diffusion. This has been achieved by the ORNL group through their time-of-flight method described in chapter 1. It is, therefore, now recognised that the study of arrival time distributions yields data for a new transport coefficient, the longitudinal diffusion coefficient D_L .

The expression used by Wagner <u>et al</u>. (1967), to determine longitudinal diffusion coefficients (equation 1.7) is

$$D_{L} = \frac{d^2 \delta t^2}{4 t_m^3} (1 - \beta)$$

Direct application of this equation can yield accurate D_L values provided that three criteria are satisfied:

(1) The total contribution to the distribution spread by factors other than diffusion (e.g. light pulse width and electronic noise) must be negligible compared with the diffusion itself.

(2) The width of the electron group at time t = 0 must be negligible in comparison with the width at $t = t_m$.

(3) Every electron arriving at the detector must have an equal probability of being recorded, i.e. there must be no discrimination against electrons arriving later in the distribution because of the dead-time of the detection system.

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In fact none of the three criteria can be satisfied adequately in practice. The influence of the first criterion can be illustrated by the following example which represents a typical experimental situation. There are three main factors that contribute to the width of the arrival time spectrum: (a) diffusion of electrons, (b) the UV pulse width and (c) the electronic noise. The contribution by diffusion is proportional to the square of the distance d and inversly proportional to the pressure P. For methane at $E/p = 0.2 \text{ V cm}^{-1} \text{ torr}^{-1}$, the contribution to the arrival time distribution width at $\frac{1}{e}$ peak amplitude and for d = 25 cm and P = 10 torr is approximately equal to ~540 ns (this value has been calculated from the data of Wagner et al.(1967) using the approximate expression for longitudinal diffusion

$$D_{L} = \left(\frac{d^{2} \delta t^{2}}{4 t_{m}^{3}}\right)$$

The second factor contributing to the spread of the spectrum is the light pulse width. Although the manufacturers of the flash tube used by Wagner et al. quote that the duration of the flash measured at $\frac{1}{3}$ peak amplitude varies from 0.5 µs to 15 µs depending upon discharge capacitance, Wagner <u>et al</u>. quote a measured flash width of about 275 ns at $\frac{1}{6}$ peak amplitude.

The third factor contributing to distribution spread is the electronic noise. Although no figure for this factor has been given by Wagner <u>et al</u>., measurements carried out with a similar electronic system in the present investigations showed that under favourable experimental conditions noise can contribute about 30 ns to the distribution spread at $\frac{1}{e}$ peak amplitude.

Clearly, the combined effect of the light pulse width and electronic noise contribute significantly to the distribution width as compared to

contribution by diffusion. It becomes more significant and perhaps dominant when the contribution by diffusion is small, i.e. at higher pressures and shorter drift distances.

The experiments of Hurst <u>et al</u>. (1963), and Hurst and Parks (1966) to measure D_L were carried out at high pressures. Since the contribution to the spectrum width by diffusion is smaller than in the case of low pressure, these workers developed a deconvolution analysis carried out on every distribution to unfold the true contribution due to diffusion from the combined effects discussed above. However, Wagner <u>et al</u>. (1967), whose measurements were made at low pressures, used a more straightforward procedure that can be explained as follows:

Assume that $T_o(t)$ is the distribution resulting from the effects discussed under headings (1) and (2), that is, the spectrum that could result if there were no diffusion. [Experimentally, $T_o(t)$ was determined when their system was completely evacuated.] The effect of $T_o(t)$ on the final distribution is to produce a smeared function E'(t), which is the convolution integral

$$E'(t) = \int_{0}^{t} E(\tau) T_{0} (t-\tau) d\tau$$
 [3.1]

Since E'(t) is the spectrum actually measured, a method of finding D_L from E'(t), rather than E(t), is needed.

Define D'_{L} (with the same formulation as for D_{L}) such that

$$D'_{L} = \frac{d^{2} \delta t'^{2}}{4t_{m}^{3}}$$
[3.2]

where $\delta t'$ is defined for E'(t) in the same way as δt for E(t) (section 1.3.2). Then

$$\frac{\mathbf{D}_{\mathsf{L}}}{\mathbf{D}_{\mathsf{L}}'} = \left(\frac{\delta \mathbf{t}}{\delta \mathbf{t}'}\right)^2$$



Fig. 3.4 The correction factor $(\delta t/\delta t')^2$ plotted as a function of $(2\delta t')^{-1}$ for the time-of-flight apparatus of Wagner <u>et</u> <u>al</u>. (1967).

The correction factor $(\delta t/\delta t')^2$ is found in the following manner. It is assumed that $\beta \equiv D_L/Wd$ is very small compared with unity and that the "un-smeared" arrival time distribution E(t) is a simple gaussian function i.e. from equation 1.6,

$$E(t, \delta t) = \text{const. } e^{-\left[\frac{t-t_m}{\delta t}\right]^2}$$

Knowing the instrumental function $T_o(t)$ for a particular apparatus, a family of smeared functions E'(t, δ t) can be calculated, using the convolution integral (equation 3.1), for various values of the parameter δ t. From these curves the corresponding values of δ t' can be obtained. The correction factor obtained in this way by Wagner <u>et al</u>. is shown in figure 3.4, where $(\delta t/\delta t')^2$ has been plotted as a function of $(2\delta t')^{-1}$.

Failure to satisfy criterion (3) arises from the fact that the dead-time of the detection system, in general, exceeds the width of the arrival time distribution. To meet this criterion, the ORNL group developed a procedure by means of which they randomly picked a single electron out of the swarm and measured its arrival time. With this procedure i.e. by keeping the ratio $C/F \ll 1.0$ (C/F is the average number of electrons counted in each event - section 1.3.2), they minimised the error arising from Poisson distortion. Figure 3.5 shows correction factor for $\frac{D_L}{U}$ due to Poisson distortion and the approximation

$$D_{L} = \frac{d^2 \delta t^2}{4t_m^3}$$

plotted as a function of

$$\frac{\delta t}{2t_m}$$
 ($\equiv \beta^{\frac{1}{2}}$), for various values of C/F.



Fig. 3.5 The correction factor for D_L/μ due to Poisson distortion plotted as a function of $\delta t/2t_m$ for various values of C/F, (Wagner <u>et al</u>. 1967).

C/F	\bar{n}_c	t_m (µsec)	δ <i>t</i> (μsec)	<i>W</i> (cm μsec ⁻¹)	$D_L \times 10^3$ $(\text{cm}^2 \mu \text{sec}^{-1})$
0	0	28.420	0.561	0.950	2.49
0.0488	0.05	28.410	0.561	0.950	2.49
0.0952	0.10	28.400	0.561	0.951	2.50
0.3935	0.50	28.340	0.554	0.953	2.46
0.6322	1.00	28.270	0.537	0.955	2.32
0.9180	2.50	28.120	0.465	0.960	1.77
0.9650	3.35	28.070	0.432	0.962	1.66
0.9930	5.00	27.990	0.387	0.965	1.24
1.0000	10.00	27.860	0.324	0.969	0.882
1.0000	50.00	27.590	0.239	0.976	0.477
1.0000	100.00	27.500	0.217	0.982	0.411

Table 3.1 Changes in W and D due to Poisson distortion (from Hurst and Parks 1966).

Thus by using the curves of figures 3.4 and 3.5 to correct for D_L , Wagner <u>et al</u>. have employed a more straightforward procedure and have overcome the use of the elaborate deconvolution analysis applied by Hurst <u>et al</u>. (1963) and (1966) to each distribution.

The pulse technique adopted by the ORNL group has been devised to provide, simultaneously, measurements of drift velocity and diffusion coefficient from the arrival time distributions. With this technique, the accuracy of the measurement of the transport coefficients, particularly D_L , depends strongly on the experimental conditions. This point can be easily illustrated by looking at table 3.1. In this table, the apparent values of W and D_L were calculated from the arrival time distributions shown in fig. 3.1 using the approximate expressions

$$W \simeq \frac{d}{t_m}$$
 and $D_L \simeq \frac{d^2 \delta t^2}{4t_m^3}$

Noting that $C/F \rightarrow \bar{n}_c$ as $\bar{n}_c \rightarrow 0$, one can easily see that for $\bar{n}_c = 1$, i.e. when, on the average, only one electron arrives at the detector in each event, the error in D_L that would arise, if the dead-time of the detection system is ignored, is 7%. The corresponding error in W is only 0.5%. For $\bar{n}_c = 100$, D_L is underestimated by about a factor of 6, while the corresponding error in W is about 4%. Therefore, great care is required in applying this technique and analysing its results.

3.4 Transport Coefficient Studies of Previous Investigations

In this section results obtained by previous workers for some gases relevant to the present work will be discussed.

The prime object of the present work is to attempt to determine

with as high a degree of accuracy as possible some of the transport coefficients of electrons in some gases and gas mixtures used in proportional chambers and counters. Among these gases, mixtures of argon and methane have found many applications. For example, soft X-ray studies are carried out at Leicester University using a two crystal spectrometer employing a pill-box proportional counter through which a mixture of 90%/10% Ar/CH4 is flown. Another mixture which has proved to be useful in counter work is Ar/75% CH4. This mixture was used in an imaging proportional counter, employed by Leicester University X-ray Astronomy group, together with a processing X-ray mirror (provided by the Space Physics group at MIT), to form a soft X-ray imaging system which was successfully flown aboard a sounding rocket. With this system the first 2D X-ray image of a supernova reminant (the Cygnus loop) was obtained (Kayat 1978).

Methane possesses very useful properties as a quenching gas in proportional counter applications. It has good stopping power and large hydrogen content. The drift velocity in methane is very large and the diffusion is small. Argon which has a relatively much lower drift velocity, moderates the motion of electrons when mixed with methane. Argon-methane mixtures appear, in general, to provide wide drift velocity saturation plateaus. As discussed in section 1.2, drift velocity which is independent of electric field can be advantageous in several counter applications.

Addition of argon to methane moderates the operating conditions. For example, the anode voltage required to operate a proportional counter using 100% methane to give a certain gas gain is greatly reduced (to give the same gas gain) when an appreciable proportion of argon is mixed with it. However, the choice of the proportions for a

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mixture depends on how suitable that mixture is, to satisfy the requirements of a particular application.

Despite the wide use of argon-methane mixtures in proportional counter applications, it is somewhat surprising to find that there are very few measurements of transport coefficients for these mixtures available.

English and Hanna (1953) have measured the drift velocity in a wide range of proportional counter gases and gas mixtures. Among these gases, they have measured the drift velocity in a range of ten argonmethane mixtures. Drift velocity data for most of the argon-methane mixtures and many of the other mixtures studied by English and Hanna does not seem to be available in the literature. For this reason and since some of the gases studied by English and Hanna are covered in the present work, their experiment will be reviewed and the accuracy of their measurement will be examined.



Fig. 3.6 Schematic diagram of the ionisation chamber used by English and Hanna (1953).

The English and Hanna experiment for determining drift velocities is based on oscilloscope measurement of the rise time of an electron pulse. These authors used a grid ionization chamber in which electrons were generated by means of a collimated α -particle source mounted on the cathode of the chamber (see figure 3.6). The gas pressure in the chamber was adjusted such that the α -tracks almost reached the grid. The grid voltage obtained from a potential divider was adjusted so that the grid was just negative enough not to capture electrons. Electrons generated by the α -particles passed through the grid and appeared as a negative pulse at the collector. The drift velocity was calculated from the range of the α -particle divided by the rise time of the electron pulse. Rise time measurements were carried out on photographic records from an oscilloscope

The method of English and Hanna appears to be very simple. However, their results contain a large number of uncertainties and analysing these results is less straightforward. The accuracy of the results of these investigators is limited by several factors, such as:-

(i) field distortion in the ionization chamber as a whole and in vicinity of the grid in particular,

(ii) timing inaccuracies, (the English and Hanna experiments required reading drift times from an oscilloscope trace which is inherently inaccurate particularly when these times are small),

(iii) poor definition of the drift distance,

(iv) uncertainty resulting from diffusive factors which have been ignored on the grounds of being small, (in general this is not true), and (v) uncertainty in the estimate of the grid-collector transit time.

For these reasons it is believed that the reliability of the results of English and Hanna is questionable. The maximum margin of error quoted by these authors is 10%. This limit of error is believed

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to be underestimated. To illustrate this point, consider their drift velocity result for methane (their result for this gas has been chosen because of the availability of data of other workers for comparison purposes). Over the range of E/p values at which English and Hanna made their measurements $(0-0.6 \text{ V cm}^{-1} \text{ torr}^{-1})$, there is a large disagreement (over 50% in some regions of the W(E/p) curve) between their results and those of Bortner, Hurst and Stone (1957), Cottrell and Walker (1965), Wagner, Davis and Hurst (1967), Pollock (1968), Nelson and Davis (1969) and those obtained in the present work. These workers have measured, independently, the electron drift velocity as a function of E/p using different techniques. The results reported by all of these workers are in good agreement. The maximum discrepancy between their results is about 7%. It seems reasonable, therefore, to suggest that the results of English and Hanna for methane are inaccurate and appear to be overestimated. [Some other results of English and Hanna, relevant to the present work, will be discussed in chapter 7.]

Diffusion coefficient measurements for counting gas, in general, are very scarce, and for the gas mixtures studied in the present work in particular they are very difficult to find in the literature.

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CHAPTER 4

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EXPERIMENTAL APPARATUS

4.1 Introduction

As discussed in previous chapters, the principle aim of the present work was to determine, with high degree of accuracy, transport coefficients of electrons in counting gases as a function of the ratio of electric field to gas pressure. This chapter describes in detail the apparatus employed.

A special feature of the present experimental approach was the ability to vary the drift distance. In drift velocity measurements this important facility enabled first order end effects to be eliminated; in the lateral diffusion measurements the facility allowed axial alignment of the system to be verified.

4.2 The drift/diffusion chamber

The chamber was so designed that it could be used to measure drift velocity and longitudinal and lateral diffusion coefficients. The principal components of the chamber were an electron source, an electric field shaping electrode assembly and a detection system. The electron source was a movable photocathode assembly from which electrons were released by UV irradiation. The field shaping electrode assembly consisted of guard annuli accurately separated by pyrex spacers and maintained at proper potential by a potential divider. The choice of the detection system was determined by the transport parameter being measured. Two different detection systems were used. Firstly, a proportional counter was used in conjunction with the electron source and the field shaping electrode assembly to measure drift velocities and attempt measuring longitudinal diffusion coefficients. With this

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Fig. 4.1 Time-of-flight apparatus. (a) Main parts.



Fig. 4.1 Time-of-flight apparatus. (b) Main dimensions.



PLATE 4.1:

Experimental chamber

- A Cathode pulserB UV-flasherC Proportional counter coupling circuit

configuration the system was similar to that used by the ORNL group in their pilot experiments (Hurst <u>et al</u>. 1963). The chamber was designed such that the proportional counter could be replaced by a Townsend-type of collector. This provided the second type of detector which was employed to measure lateral diffusion coefficients.

Figures 4.1(a) and (b) show, respectively, the main parts and main dimensions of the time-of-flight apparatus (see also plate 4.1). The housing of the system which was made of stainless steel tube of internal diameter 127 mm, consisted of two main sections provided with identical flanges. A third section (of the same lateral dimensions as the main sections of the housing) containing the plane, Townsend-type, collector could be fixed to the bottom flange to replace the proportional counter shown in figure 4.1(a), (the plane collector is shown in a separate diagram, figure 4.4). In between adjacent flanges 0-ring seals were used to provide a leak-tight system. The chamber was provided with three similar gas flow stainless steel tubes of diameter 6.35 mm. Two of these were used for gas inlet and outlet and the third was connected to a pressure gauge.

In choosing the dimensions of the various parts of the chamber careful attention had to be made to a number of parameters, however, the final choice was a compromise that resulted in a versatile system. Choice of the materials used in the construction of the chamber was another important factor considered. The major component used was non-magnetic stainless steel, other materials used were pyrophyllite, pyrex and berightium-copper; the use of organic materials was minimal since these are known to outgas excessively.

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4.2.1 The photocathode assembly

The final form of photocathode assembly adopted for drift-velocity measurements is shown in figure 4.2 (for lateral diffusion measurements this assembly was slightly modified, see section 4.2.4). The main part of this assembly was a stainless steel cylindrical head of outer diameter 38 mm. The head consisted of two halves, each was 25 mm in length. The base of the lower half was a stainless steel disc with a circular aperture of 6 mm diameter. Mounted on the aperture was a flat copper micromesh (supplied by EMI Electronics Ltd., U.K.), of optical transmission 42% and aperture 11 µm. The disc containing the copper micromesh (will be termed hereafter as the grid), was evaporated with gold to minimize contact potential differences. The inside wall of the lower half of the photocathode head was insulated with a thin, open ended cylindrical layer of perspex. Two 8 mm diameter holes were drilled through the wall and the insulator on opposite sides to ensure good gas circulation. A perspex ring of internal diameter 30 mm and thickness 2 mm was placed on the grid. This ring acted as an insulator between the grid and a photocathode disc. The photocathode was similar to that suggested by Moruzzi (1967). It consisted of a quartz disc of diameter 35 mm and thickness 1 mm; with an evaporated gold coating, 400°A on the lower surface. This surface could be irradiated from above by a UV source placed outside the chamber. UV radiation was fed along a flexible light guide. Electrons were released from the irradiated gold surface, passed through the thin gold film and emerged from the non-illuminated surface. A number of gold layer thicknesses, ranging from 100°A to 600°A, was tried. The final choice was a trade off the ability of the gold layer to stop the UV photons from being transmitted through to the drift region and the release of a sufficient number of

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electrons. Of the range tried the 400°A layer was found to produce satisfactory results. Electrical contact with the gold layer was made through a conducting stainless steel ring (thickness 0.2 mm and internal diameter 30 mm), on which the photocathode disc was placed. On the outer circumference of this metallic ring a long tag passed vertically to the cavity above the photocathode disc through a small flat area ground off the circumference of the disc. The tag was used for electrical connections. All grid cathode parts were held in position by means of a spiral spring of approximately equal diameter to that of the internal cylindrical cavity. The other end of the spring was pressed against a perspex separator, tightly fitted between the two halves of the photocathode head. To the inside top edge of the lower half of the head a further tag was spot welded to provide electrical contact for the grid. Both tags were connected to PET connectors fixed on the top of the apparatus. The flexible light guide, which was supplied by Schott (West Germany), was 250 mm long and had a fibre bundle of diameter 1 mm. For these dimensions the manufacturers quote the following characteristics:

Angle of aperture is $32 \pm 5^{\circ}$ at wavelength $\lambda = 2540^{\circ}A$. The light transmission at this wavelength is approximately 50%. The minimum bending radius is 27 mm.

The ends of the fibre bundle were secured within metallic ferrules and placed into flexible metallic tubing. One end of the light guide was fixed into a hole of 4 mm diameter drilled through the centre of the perspex separator. The light guide was then passed through a slot cut along the wall of the upper half of the photocathode head. The other end of the light guide was exposed to the outside of the chamber by passing it through a tube on the side of the topmost section of the

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housing. The presence of this section of the housing made it convenient to assemble and dismantle the photocathode assembly and allowed enough room for the movement of the light guide. Leak-tightness of the side tube containing the exposed end of the light guide was ensured by employing a Wilson-seal at its end.

The photocathode head was held in a central, vertical axis by means of a stainless steel rod 200 mm long and of diameter 6.35 mm (fig. 4.1). The rod was bolted on the top of the photocathode head. Accurate alignment was ensured by precision machining and by passing the rod through two metallic guides, each was 10 mm thick. The first guide was in a form of a bearing made of brass to minimize wearing of the rod. The brass bearing was bolted into the centre of a thick stainless steel disc welded to the body of the chamber and in a plane parallel to the top. The second rod guide, which was 40 mm above the bearing, was the chamber top itself. The rod passed to the outside of the chamber through a further Wilson seal. Its movement was restricted along a vertical axis only, i.e. no rotation was possible. The movement of the rod (i.e. the photocathode), was controlled by a micrometer screw gauge whose spindle's end was held against a ball bearing fitted into a cap that was, in turn, fitted onto the top end of the photocathode rod. The micrometer was held by a rectangular support bolted on the top of the chamber. The ball bearing at the end of the photocathode rod was always held against the end of the micrometer spindle by two spiral springs. The springs were stretched such that their lower ends were hooked on two oppositely situated side arms fixed to the rod, and their upper ends were hooked on two holes in the top of the micrometer support.

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4.2.2 The field shaping electrode assembly

Production of a uniform longitudinal electric field can be achieved by employing a series of guard electrodes maintained at voltages appropriate to their position along the length of the field. Field distortion can occur as a result of a number of factors. The factors affecting the uniformity of the field in a cylindrically symmetric guard electrode systems of the types often used in swarm experiments, have been examined and discussed elaborately by Crompton, Elford and Gascoigne (1965). These authors suggest that measured transport coefficient values, particularly D, are sensitive to field distortions.

Four possible causes of field distortion should be considered. Firstly there may be inaccuracies in the geometrical structures of the field shaping electrodes, the electron source electrode or the receiving electrode. Secondly, field distortion may arise from incorrect voltage division in the potential divider feeding the potentials to the guard electrodes. Thirdly, contact potential differences cause field distortions, the effect of which is rather serious at low electric field values because the degree of non-uniformity caused by this factor is inversely proportional to the field strength. Finally, field distortion may result from penetration of stray fields outside the guard electrode assembly.

The system employed in the present work was so designed that measurements could be made under conditions of constant electric field of maximum uniformity. Under ideal conditions the drift time from the photocathode to the anode is directly proportional to the distance between these two electrodes. In practice ideal conditions can not be realised over the whole chamber particularly in the vicinity of the

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boundaries of the electron flight path. However, ideal conditions could be approximated by eliminating, as far as possible, the causes of field distortion. Therefore in the present system identical, closely spaced guard annuli with minimal thickness and large lateral depth, were used. The use of thin annuli was desirable to avoid field distortion due to finite electrode thickness. This was particularly important in the present system since the inner diameter of the annuli was small. Closely spaced annuli with large lateral depth had to be used in order that adequate shielding could be achieved. The dimensions of the drift region were chosen as follows:

The drift distance was variable and could be set accurately by moving the electron source over a range of 20 to 50 mm.

Internal diameter of guard electrode	=	40 mm
External diameter of guard electrode	=	80 mm
Thickness of guard electrode	=	0.5 mm
Thickness of guard electrode's spacers	=	4.5 ± 0.01 mm
Internal diameter of enclosing envelope	=	127 mm

The schematic diagram of figure 4.3 shows a cross-section of the drift region in the plane of a guard electrode. The diagram also shows the diameter (drawn approximately to scale) of the photocathode head and the guard electrode relative to that of the enclosing envelope.

Choice of the materials used in constructing the system played an important rôle in satisfying the requirements of high field uniformity. For example, the choice of non-magnetic alloys was rather important. In addition, since the thickness of the guard electrodes was small, their construction required a metal or alloy of high mechanical rigidity to ensure minimum geometric inaccuracies. An alloy that satisfied this

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requirement was berillium-copper from the annuli were made.

Another requirement was to ensure minimum field distortion at the ends of the drift region. These areas were particularly susceptible to field distortions because (time-of-flight system) of possibility of penetration of the anode field into the drift region at one end, and the effect of the cathode pulse (see section 4.3.3) at the other. To minimize field distortion in these regions gold coated copper micromesh grids of the type described in section 4.2.1 were used. [The photocathode grid was described in the preceding section.] In the boundary between the drift region and the proportional counter a further micromesh grid was used. This will be described in the next section.

The use of a flat plate collector for lateral diffusion measurements (Townsend method) gives rise to field distortions in its vicinity. These distortions may result from the finite size of the circular gap between the central collector and the outer annulus and contact potential differences. In the collector used in the present work field distortions due to these two factors were minimized by making a gap of minimal width and by coating the collector with gold (see section 4.2.4).

A further requirement for minimizing field distortion was to avoid penetration through the guard electrodes of stray fields outside the electrode structure. Electrodes with close separation and large lateral depth provided adequate shielding. Huxley and Crompton (1974) remark that field distortion can arise from the proximity of the envelope (either glass or metal), when an open electrode structure is used. To avoid distortion of this kind the stainless steel section of the housing surrounding the field defining electrode structure was kept 22.5 mm away from the guard annuli (figure 4.3).

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Fig. 4.3 A section across the field-shaping assembly (drawn approximately to scale).

On the basis of the above discussion the drift region section of the apparatus was constructed in the following manner:

The section of the housing enclosing the drift space was of the same cross-sectional dimensions as described in section 4.2.1. Its length however was 110 mm. On the inside wall of the housing a thick stainless steel annulus was welded parallel to the base flange and 55 mm from it. This annulus acted as a support for the guard electrode assembly. The guard rings were supported by three pyrex rods of diameter 6.35 mm. The rods passed through three equally spaced holes drilled in each ring. The rods were provided with larger diameter cylindrical heads on which the bottom guard ring rested. The field electrode assembly consisted of ten guard rings arranged such that adjacent rings were separated by means of hollow cylindrical pyrex spacers slided (tight fit), on the supporting rods (i.e. 3 spacers per ring). The spacers were of equal lengths (4.5 mm) and had been matched to within 0.01 mm by grinding. The rods, with all the rings on, were passed through three corresponding holes that had been drilled into the annular stainless steel support mentioned above. The whole assembly was held in position by means of three steel springs slided on the top ends of the rods and pressed against the top surface of the annular support on one side and against flat clips (inserted into circular grooves at the top of the rods), on the other. The resulting structure was such that the entire electrode assembly was rigid and all the annuli were parallel and well aligned.

The potential divider supplying potentials to the guard electrodes was made of a chain consisting of ten 1 Mohm, $\frac{1}{4}$ W, carbon film resistors type, Mullard CR25. The resistors had been matched to better than 0.2% and were connected in series between earth and the top guard

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electrode with one resistor between every two adjacent electrodes. The lower 4 resistors of the potential divider (i.e. connecting the bottom four rings through to earth) were enclosed within the apparatus. The rest of the chain continued outside the chamber. The external resistors were connected between leadthroughs (glass-to-metal seals) fitted on the wall of the housing. These, in turn, were connected to the remaining rings inside the apparatus. Since one of the main features of the present system was the variable drift length, these external connections provided the required drift length with the appropriate voltage; e.g. when a drift field, 200 V cm⁻¹ was required, 1 KV had to be applied to the 5.0 cm position, 800 V to the 4 cm position and so on. Drift voltages were fed to the electrodes via PET connectors fixed on a curved metallic shield bolted on the outside to the body of the apparatus. Extension wires were used to connect the PET connectors to the leadthroughs (see figure 4.1).

Along one side of the drift region section of the housing a glass window 3 mm thick, 60 mm long and 30 mm wide was made. The window was araldited onto a flat frame welded on the wall of the housing. The purpose of the window was to allow visual observations of the internal parts and was used for drift length calibration.

4.2.3 The proportional counter

The detection system associated with the electron source and the field defining electrode structure for measurement of drift velocity and longitudinal diffusion was a pill-box proportional counter. This set-up was similar to those used by the ORNL group. In their pilot apparatus Hurst <u>et al</u>. (1963) used a counter operating in G-M mode as a detector. As a consequence measurements were restricted to gases and

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gas pressures suitable for the operation of such detectors. In later work the ORNL group modified their apparatus, (Wagner <u>et al</u>. 1967), so that an electron multiplier could be used, thus removing both restrictions.

In the present work since the aim was to measure drift velocities and longitudinal diffusion coefficients in counting gases only, an obvious choice for a detector was a proportional counter. The counter was constructed of stainless steel with the following dimensions:

> Internal diameter of counter = 70 mm depth of counter (2h) = 25 mm diameter of anode wire $(2r_a)$ = 50 µm

The counter was bolted, through its flange, to a solid stainless steel disc of thickness, 8 mm. The disc, whose diameter was the same as those of the flanges of the housing, was in turn bolted to the base flange of the drift region. O-rings seated into grooves between the counter and the separating disc, and the disc and the drift region ensured that these areas were leak-tight.

The anode was made of 50 µm diameter tungsten wire stretched, diametrically between two glass-to-metal seals, half-way across the depth of the counter. The glass-to-metal seals were identical to those mentioned earlier in connection with the drift region. This type of seal had been specially made for gas filled detectors used by the X-Ray Astronomy group at Leicester University. Being hygienic and of superior breakdown characteristics, these seals were quite suitable for the counter used in the present work.

The counter was provided with two of the three gas flow tubes mentioned in section 4.2. The two tubes were situated diametrically opposite and at right angles to the anode wire. To ensure adequate gas

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circulation the proportional counter was connected to the main body of the apparatus through two holes drilled in the separating disc directly above the flow tubes. The separating disc was provided with a circular recess at its centre and on the top surface (see fig. 4.1a). The recess had a diameter 5.0 cm, lateral depth 1.0 cm and longitudinal It was machined such that a disc (will be termed heredepth 3.0 mm. after 'the aperture disc') could be plugged tightly into it making the whole surface level. A set of five aperture discs was made. Four of these had circular apertures of diameters, 1 mm, 2 mm, 5 mm and 10 mm, drilled through their centres. The fifth aperture disc contained a rectangular slit, 10 mm long and 2 mm wide. A series of experiments was carried out to examine the effects, of the aperture shape and size, on the drift velocity and longitudinal diffusion measurements. In some of these experiments the apertures were covered with micromesh grids. The aperture that was finally adopted for drift velocity measurements was the rectangular slit covered with a micromesh grid. The aperture disc containing the slit was fitted into the recess such that the length of the slit was parallel to the anode wire. The results of the experiments carried out using the various apertures will be discussed in section 6.4.2.

Knowledge of the proportional counter's field was necessary in assessing some of the effects influencing the accuracy of drift velocity measurements (section 5.3.2). For a pill-box counter the electric field, Ey, at the aperture is approximately given by,

$$E_y = \frac{\pi/2h}{\log_e (4h/\pi r_a)} \cdot V_a$$

where 2h is the counter depth V_a is the anode voltage

 r_{a} is the anode wire radius.

For the dimensions quoted above, E_y amounts to about 0.2 Va.

The proportional counter was mounted in an aluminium cylindrical shielding box (figure 4.1).

4.2.4 The plane collector for lateral diffusion system

The method used in the present work for measuring lateral diffusion coefficients was the conventional Townsend method. The chamber employed to measure this parameter was essentially that used for measuring the drift velocity. The only major difference was the replacement of the proportional counter used in connection with drift velocity measurements by a flat plate collector.

Figure 4.4 (see also plate 4.2) shows a diagram of collector adopted in this work. In choosing the dimensions of the various parts of the collector a number of considerations had to be taken into account. These can be discussed on the basis of the principle of the method which was outlined in section 1.3.1. The ratio R of the current, i_b received in the central collector to the total current i_T is given by

$$R = \underline{i}_{b} = 1 - \underline{h}_{d} e^{-\frac{W}{2D}}$$
 [4.1]

where h is the drift distance, b is the radius of the central collector, and d is given by

$$d = (h^2 + b^2)^{\frac{1}{2}}$$

Assuming that $\left(\frac{b}{h}\right)^2 \ll 1$, then equation 4.1 may be written as







PLATE 4.2: Townsend-type collector.

$$1 - R \simeq \frac{h}{d} e^{-\frac{W}{2D} \cdot \frac{b^2}{2h}}$$
[4.2]

In the present system h could be varied within a range of 2.0 to 5.0 cm. The choice of b and $\frac{b}{h}$ was determined by the ability of the current measuring system (see section 4.4) to determine the ratio, R with adequate precision. The value of R corresponding to some E/p value for a certain gas is also a function of the ratio of $\frac{W}{D}$. For a constant field E, $\frac{W}{D}$ is proportional to $\frac{D}{u}$ (μ is the electron mobility = $rac{W}{E}$). Theoretical calculations of $rac{D}{\mu}$ for the gases studied in the present work and for the range of E/p of interest (0.1 to 1.0) V cm^{-1} torr⁻¹, indicated that this parameter covered a wide range of values, from 0.025 V to 1.4 V. The restriction imposed by the $^{D\!/\mu}$ values near the lower limit requires that small values of b and large values of h must be used if a significant fraction of the current is to arrive at the receiving electrode outside the central collector (section 5.4 discusses how this problem was partly overcome). With upper value of h being limited, in the present chamber, to 5.0 cm, the final choice of b was a compromise, such that the largest possible D/μ range, for gases studied in this work, would be covered. The value of b chosen was 1.25 mm.

The width of the circular gap between the central collector and the outer annulus is an important parameter. Incorrect choice of this width may lead to significant errors. In previous investigations it was usually assumed that the electrons arriving at the gap divide equally between the central collector and the annulus. The accuracy of this assumption is difficult to assess since the manner in which electrons diffuse within the gap is unknown. Any error arising from this assumption may be minimized by making the gap as narrow as possible. In the present collector a gap of width 10 µm was made. To avoid any

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significant effect on the current by high inter-electrode capacitance, the annulus was undercut as shown in figure 4.4.

The outer annulus had a diameter, 38 mm and thickness 4.5 mm. In the original design the annulus was divided into four quadrants. With the use of a switch each quadrant could in turn be connected to the current measuring equipment while the others were grounded. They could also be connected together as one unit. The purpose of this feature was to ensure a uniform electron distribution over the whole receiving surface. But owing to practical difficulties arising from leakage resistance and by using an alternative procedure for aligning the system (section 6.6.1), the quadrants were electrically connected together directly to the current measuring system and this facility was not used.

The guard electrode was similar to those used in the field shaping electrode assembly and was separated from the collector annulus by a gap, 1.0 mm wide.

The supporting structure of the electron collector was made of pyrophyllite. This structure consisted of two main parts; an inner part was used for supporting the quadrants and an outer part was used to support the central collector. A standard workshop treatment of pyrophyllite yielded hard smooth surfaces. The guard electrode was fixed on the outer pyrophyllite support such that it was level with the collector. The whole assembly was bolted onto an aluminium holder which was, in turn, fixed on the base plate of the chamber. The base plate was made of non-magnetic stainless steel and was provided with two pairs of adjusting brackets that were used for aligning purposes. With this facility it was possible to move the entire receiving electrode assembly, with respect to the rest of the diffusion chamber,

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along two perpendicular axes. Movement along the axes of the adjusting brackets was restricted to ± 1.0 mm with respect to the geometrical axis of the chamber. This movement was allowed for in the fixing holes of the baseplate and the base flange. The baseplate was also provided with five glass-to-metal seals for electrical connections of the quadrants and the central collector to the current measuring equipment.

In making the various parts of the collector, precision machining, grinding and polishing ensured high order coplanarity and surface finish. Before the collector was assembled all parts had been cleaned thoroughly by ultrasonic agitation. The parts were then assembled in a clean room where the top metallic surfaces of the assembly were evaporated with gold. The whole assembly was housed in a stainless steel tube with the same diameter and identical flanges as those of the main housing (section 4.2).

In addition of the introduction, in the chamber, of the flat receiving electrode described above, it was necessary to carry out some minor modifications on the photocathode assembly. Equation 4.2 has been derived by assuming that electrons originate from a point source. Therefore it was required, in the present system, to replace the 6.0 mm diameter grid used in the drift velocity set-up (see figure 4.2) by a point source. In practice there is a lower limit to the diameter of the source hole set by the requirement that sufficient electron current be transmitted. In this work since the radius of the central collector was small, a source of minimal size was desirable. Five source holes of diameters 0.75, 0.9, 1.0, 1.25 and 1.5 mm were tried. The two largest holes were tried initially to examine the performance of the system. The diameter that was finally chosen was 0.9 mm. The source hole was drilled in the centre of a beryllium-copper disc with a diameter 37.5

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mm and thickness, 0.5 mm. The disc was coated with gold to reduce the effects of contact potential differences.

Further modifications were carried out on the photocathode assembly. The cathode-source separation was reduced from 2.0 mm to 1.0 mm. This was necessary to maintain an electric field, in the cathodesource space, of approximate value as the drift field (the voltage applied to the cathode was limited by the maximum output of the square wave generator, 12 V - see section 4.4). The importance of this was to ensure that the energy distribution of the electrons entering the diffusion space approximated closely the equilibrium energy distribution throughout the chamber. Another modification carried out was the introduction of a thin metallic washer with a larger lateral depth (6.0 mm internal diameter), to replace that employed to provide electrical connection to the photocathode used in the drift velocity set-up. This was to improve the electric contact to gold layer and hence enhance the initiation of electrons. Obviously since we were only interested in the central area of the photocathode, introduction of this washer did not affect the measurements. The photocathode disc used in this experimental set-up was coated with a 200°A layer of gold (instead of the 400°A layer used in the drift velocity apparatus) to increase its efficiency.

4.2.5 Gas handling system

This can play a major rôle in contaminating swarm chambers. To avoid such contamination a number of considerations had to be taken into account:-

(a) Mode of operation: the system used was operated in a continuous gas flow mode. This was important to avoid build-up of contamin-

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ants resulting from outgassing. Thus continuous flow ensured flushing away small traces of impurities. Using this mode of operation measurements were carried out at various pressures ranging from 50 torr to atmospheric. The rate of flow was governed by four control valves positioned at suitable parts along the flow line.

(b) Choice of material: flow channels to and from the chamber were made of materials with low outgassing levels. Mainly glass and stainless steel tubings were used. These were connected by means of short lengths of flexible tubing. Two types of flexible tubing were tried; PVC and silicon rubber. Silicon rubber tubing is known to be more hygienic than the PVC. However, being much softer than the PVC, silicon rubber suffered from collapsing when the system was operated in the continuous flow mode at reduced pressures. This made it rather difficult to control the pressure of the system. An experiment was carried out to investigate the effect of impurities introduced by PVC on drift velocity measurements for A/10% CH4, using purposely a 30 m long PVC flow line. In that experiment no significant change in drift velocity values (as compared with measurements using a substantially shorter length of PVC tubing), was observed (see section 6.3.1).

(c) Leak tightness: atmospheric contaminants can have serious effects on transport coefficient measurements. Therefore, to avoid such effects precautions had to be taken to prevent atmospheric contamination of the chamber. Flexible connecting tubings were fitted tightly on the stainless steel (or glass) tubes of the flow line. Further, these connections were secured by cylindrical adjustable clips that could be tightened as required. The number of connections along the flow line was kept to a minimum. The system was regularly tested for leaks using two methods, leak sniffer method and vacuum test.

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As mentioned in section 4.2, the chamber was provided with three flow points, an inlet, an outlet and pressure gauge connecting point. At one end of the inlet channel of the flow line the gas, being studied, passed from the cylinder through a laboratory gas regulator type "Diadem" DML-2, supplied by The British Oxygen Company (BOC). This type of regulator was helium leak tested. The manufacturers claim that its leak rate is 10⁻⁷ torr litre per second. The regulator was provided with two valves that controlled the gas pressure and flow. The outlet of the regulator was then connected to the inlet of a drying trap. The drying trap was made of a pyrex tube about 60 cm long and of diameter, 5 cm. The ends of this tube were tapered and fused to short lengths of further pyrex tubes of outer diameter 6.35 mm. The main body of the trap had been filled with successive layers of glass-wool and phosphorous pentoxide (P_2O_5) . P_2O_2 is a strong drying agent and was used by Cottrell and Walker (1965) for drying gases similar to those studied in the present work. To prevent phosphorous pentoxide particles from being sucked out of the trap under vacuum or reduced pressures, thick layers of glass-wool were placed at the ends of the main body of the drying trap. At the outlet of the drying trap a vacuum type glass stopcock provided a further flow control. Finally, the other end of this flow channel was connected to the inlet of the chamber situated at the side of the proportional counter.

The second flow point of the chamber was also situated at the side of the proportional counter opposite to the inlet. This point was connected to a pressure gauge. Gas pressures were measured by precision absolute pressure gauge type AI.101 supplied by Appleby and Ireland (U.K.). This was a capsule type with a multi-turn, twin-pointer, direct reading type, measuring from 0 to 1000 torr absolute with an

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accuracy of ± 5 torr. The capsules and the connecting tubes of the gauge through which gases flowed were made of stainless steel.

Depending upon the pressure being used, the outlet of the chamber could either be connected to a flowmeter or a rotary vacuum pump. The flowmeter was used in connection with measurements carried out at atmospheric pressure. It was type R-2-15-AA, supplied by Brook Instruments, N.V. (Holland). It was provided with a sapphire float (see figure 4.5 for calibration curve). The outlet of the flowmeter was connected to one end of a glass tube by a short PVC tubing. The other end of the glass tube was dipped under the surface of a light oil contained in a small bottle. For reduced pressure measurements the outlet of the chamber was connected to a rotary vacuum pump. For this mode of operation the outlet channel was provided with another pressure control valve situated between the outlet of the chamber and the inlet of the pump. With the use of the four control valves described above it was possible to set the gas pressure as required and control it to within ±1 torr while maintaining a continuous flow operation.

4.3 Electronics associated with the time-of-flight apparatus

The electronics used in the present work comprised two separate systems. The first system was associated with drift velocity and longitudinal diffusion measurements and the subsidiary work carried out in connection with these measurements. That is, time and voltage calibration, noise measurement and general apparatus optimization. The second electronic system was used in connection with lateral diffusion measurements. Most of the units used were conventional electronic modules, therefore detailed circuits of these units will not be given here. However, some of the units employed were designed and constructed

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especially for this work and these will be discussed in detail.

Figure 4.6 is a block diagram of the electronic system associated with the time-of-flight apparatus. The basic principle of the method was similar to that developed by the ORNL group. Swarms of electrons were initiated by pulsed UV light from the photocathode, the flash tube being triggered, at a suitable repetition rate, by the pre-pulse of the master pulse generator. The main output pulse from the generator was fed to both the cathode pulser and the 'START' input of the timeto-amplitude converter. The delay between the pre-pulse and the main pulse of the master pulse generator was adjusted so that the cathode pulse occurred during the maximum UV intensity of the flash tube. (The cathode pulse duration was much shorter than the UV output duration.)

The stop pulse for the T.O.F. measurement was produced by the detection of an electron by the proportional counter. The counter was connected to a charge sensitive amplifier, a bipolar filter and a crossover detector. This detector triggered the 'STOP' of the TAC. Measurements were carried out in both coincidence and anti-coincidence modes. With the former mode a single channel analyzer (SCA) had to be used to discriminate against large pulses that had resulted (in some cases) in double-peaked distributions (see section 6.5.6). The output of the TAC was then connected to a pulse height analyzer (PHA) that was accurately time calibrated (typical channel width, i.e. time interval per channel, 7.69 ns). The time-of-flight distribution was automatically recorded by the PHA during several minutes of operation. The data stored in the PHA was recorded with a teleprinter and simultaneously punched on a paper tape for computer analysis. The data could also be plotted with an X-Y plotter. The operation was continuously monitored with a double trace oscilloscope.

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Fig. 4.6 Time-of-flight electronic system.

After this brief description of the basic electronic system as a whole, we now proceed to discuss the functions and characteristics of the individual modules employed; beginning with those in the start channel.

4.3.1 The master pulse generator

This was a 'Venner' pulse generator, type TSA 628. The manufacturers quote the following characteristics:

Frequency range - 2.5 Hz to 2.5 MHz
Main pulse polarity - positive or negative with respect to earth
Max. main pulse amplitude - 20 V
Pulse width range - 100 ns to 10 ms
Delay of 'main pulse' with respect to 'pre-pulse' is variable ranging from 100 ns to 10 ms.
'Pre-pulse' can also be set with either a negative or positive polarity with respect to earth with an amplitude 7.5 ± 2.5 V (unloaded).

4.3.2 The flash trigger circuit

The pre-pulse from the master pulse generator was employed to trigger a second pulse generator (another Venner TSA 628). The function of this pulser was to feed the SCR trigger gate of the flash tube with the required pulse amplitude and polarity, +20 V.

The UV source was an Egerton, Germeshausen and Grier (E.G&G) type 108 AU xenon filled flash tube mounted in an E.G&G 'LITEPACK' type FY5. The flash tube was operated by the trigger circuit shown in figure 4.7. Values of the components R and C were determined by the experimental conditions required; i.e. the maximum repetition rate F, and the UV light intensity. The first requirement was satisfied by choosing the values of R and C such that

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Fig. 4.7 UV-light trigger network.

RC (=
$$\tau$$
) $\ll \frac{1}{F}$

where τ is the recovery time for the discharge capacitors C.

The second requirement had to satisfy the counting efficiency (C/F) criterion (Hurst <u>et al</u>. 1963). The flash tube power input, W, is given by

$$W = \frac{1}{2} C V_{dc}^2 F$$

The average power input, W, specified by the manufacturers of the tube is 7 watt. Thus, for a repetition rate, 200 Hz, and V_{dc} , 1 KV; the value of C is 0.07 μ F.

On these lines the values of R and C chosen were 12 K Ω and 0.05 μ F respectively giving a recovery time τ , 0.6 ms. This choice provided a wide range of operational frequencies and adequate UV intensity. Therefore, by changing the value of F it was possible to control the counting efficiency such that $\frac{C}{F} \sim 0.1$.

4.3.3 The cathode pulser and the biasing network

In the preliminary stages of this work, the start pulse was monitored by a photodiode. The set-up, then, closely resembled that of Hurst <u>et al</u>. (1963). The photodiode, and the flash tube, were identical to those of the ORNL group (1963). The light pulse width at $\frac{1}{e}$ peak amplitude (2V) measured with the photodiode was ~625 ns. Since the expected contribution to the T.O.F. spectrum, by diffusion in counting gases, was substantially smaller than this light pulse width, a need arose for employing a much narrower pulse, (for complete discussion the reader is referred to section 3.3.2). On these grounds the idea of superimposing a narrower electronic pulse on the light pulse was sought.

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V0.4+

Fig. 4.8 Circuit diagram of the cathode pulser.

A cathode pulser was then designed and built. Figure 4.8 shows the circuit diagram of the cathode pulser employed. The pulser provided pulses of risetime and falltime ~5 ns. It was fed from the master pulse generator (main output), with a pulse of amplitude, 3.0 V, and width 1.0 μ s. The output pulse of the cathode pulser was of an amplitude, 40 V, and its width could be varied over a range 20 ns to 120 ns (6 settings). Although these settings were relatively small, the effective 'open' duration could be adjusted to a much smaller value (~ a few ns). To explain this point consider a group of electrons at the photocathode. For this group to be transmitted through the grid, the cathode pulse width has to be greater than the time required by the group to traverse the cathode-grid space. Supposing that the group is travelling with a velocity 5 cm. μ s⁻¹, therefore it requires 40 ns to traverse the 2.0 mm cathode grid separation. Thus the effective open duration, (i.e. the real contribution to the distribution spread by the pulse), is the difference between the cathode pulse width (dial setting), and the transit time of the group from the cathode to the grid.

Although the pulse widths were accurately determined by precision calibration of the cathode pulser, the cathode-grid transit time could not be determined as accurate. This is because drift velocity data for a certain gas did not strictly apply to the cathode-grid region where the field was non-uniform, particularly in the presence of a cathode grid bias (see below).

In the preceding section we have seen that one mechanism for controlling the counting efficiency $\frac{C}{F}$ was by adjusting the repetition rate F. Clearly from the discussion above, the system count rate could also be controlled by the pulse width setting. This was a second mechanism with which $\frac{C}{F}$ was controlled. A third mechanism employed was the appli-

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Fig. 4.9 Cathode/grid biasing network.

cation of a DC bias voltage between the cathode and the grid. The bias could be adjusted to reduce the count rate of the open condition (i.e. zero bias), such that the $\frac{C}{F}$ criterion was satisfied. Although it aided in controlling the counting efficiency, the cathode grid bias main function was to prevent passage of electron swarms except when the rectangular voltage pulses were applied to the cathode. Application of the voltage control pulse on the cathode in the presence of the bias, neutralized the cathode and thereby permitted passage of the electron swarms through the grid.

The cathode-grid bias circuit is shown in Fig. 4.9. It was provided with ten settings ranging from 2.7 V to 27.0 V in steps of 2.7 V.

Experiments to illustrate the effects of repetition rate, pulse width and cathode-grid bias on the transmission of electrons through the grid will be discussed in section 6.5.3.

The start pulse from the master pulse generator was fed to the 'START' input of the time-to-pulse amplitude converter through an inverter-shaper (Fig. 4.10), that provided the TAC with the pulse shape and size it required.

4.3.4 The stop channel

The proportional counter anode voltage was supplied by I.D.L. EHT unit type 532/D, 30 KV. The EHT supply was connected to the anode wire through a 40 M Ω coupling resistor (see Fig. 4.11) for regulation. The counter capacitance in series with the coupling resistor R acted to differentiate the output pulse of the counter. The function of the capacitor C, (5000 pF, 3 KV) however, was mainly to strip off the DC high voltage from the signal, i.e. to couple the anode signal to the

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Fig. 4.10 Circuit diagram of inverter/shaper.



Fig. 4.11 Proportional counter coupling circuit.

preamplifier input. The coupling circuit was shielded in a dicast box mounted on one side of the counter. The anode was connected to the coupling circuit by a shielded wire a few centimeters long.

Choice of the preamplifier used in this work was mainly determined by its noise performance and risetime. On these lines a home-made preamplifier was chosen for this application. Its basic circuit was essentially that of an ORTEC model 118A charge sensitive preamplifier. It had a low noise performance and particularly fast rise time. The essential parameters of the preamplifier used were as follows:

> calibration input $C_T = 1.0 \text{ pF}$, 100 Ω feedback capacity $C_f = 1.0 \text{ pF}$ minimum measured noise = 210 (rms) electrons risetime = 11 ns (63%)

(see section 6.5.1 for details of noise measurement)

The preamplifier was provided with a shorting switch connected across its input to protect the sensitive FET input stage from EHT switching transients.

The preamplifier output was connected to the input of a linear amplifier for pulse shaping. The linear amplifier was an ORTEC NIM unit, model 452 operated in a bipolar mode. It was provided with the following controls and specifications, (from the manufacturers manual):

6-position switch for shaping, selecting time constant, T (0.25, 0.5, 1.0, 2.0, 3.0 or 6.0 μ s), time to bipolar zero crossing, 2.8 T; crossover time walk, 2 ns for 100:1 dynamic range; fine gain, 10-turn precision potentiometer for continuously variable direct reading gain factor of X0.5 to X1.5; coarse gain, 9-position switch selecting gain factors of X5, 10, 20, 50, 100, 200, 500, 1 K or 2 K; noise level, with T = 3.0 μ s and coarse gain > 100, (for the bipolar filter) <7.0 μ V.

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Fig. 4.12 Circuit diagram of crossover detector.

The output of the bipolar filter was then connected to the input of a crossover detector. Choice of the crossover detector was of an utmost importance. Time-of-flight systems depend, for accurate measurement, on extracting the most accurate timing information from the electronics. When such systems employ the zero-crossing technique the crossover detector is the most critical unit in their electronics. It is important that it should not be sensitive to input pulse amplitude variations over a large dynamic range.

The principle of operation of the crossover detector is well known. Thus, detailed description of this unit will not be given here. The crossover detector used in the present work was a N1M module identical to that employed by T. Harris (1972) in a similar work. Its circuit was based on the design used by Alison and Draper (1965), (figure 4.12 shows the circuit diagram of the unit used). The optimum operating point of the crossover detector was determined by two settings; the threshold of the input pulse and the tunnel diode bias. The threshold had to be adjusted for every individual gas studied such that the level was well above the noise and yet not so high as to run into serious overload of the linear amplifier. This adjustment was necessary because the counter had different operating conditions (e.g. EHT) for different gas fillings. It was not, however, always necessary to make such adjustment to the tunnel diode bias setting because the crossover point was very insensitive to pulse height. It was verified that the time of crossover was independent of pulse height (to within 30 ns) for pulse heights from threshold v_t (~5.0 mV) to about 42 mV (see sections 6.5.1 and 6.5.2).

The output of the crossover detector was fed to the 'STOP' input of the TAC via the shaping network shown in figure 4.13. The shaper

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Fig. 4.13 Circuit diagram of the shaping network used in the stop channel.

provided the pulse size and shape required by the TAC.

4.3.5 Readout electronics

The pulses from the start and stop channels described above were fed into the 'Start' and the 'Stop' inputs of a time-to-amplitude converter (TAC). The TAC provided a bipolar output signals whose amplitudes were proportional to the time differences between 'Start' and 'Stop' inputs. The instrument used here was an ORTEC, NIM unit model 437A. The manufacturers quote the following specifications:

time resolution	- 0.01% of 'Range'
temperature stability	- ±0.015%/°C
maximum start input count rate	- 3×10^6 counts/sec.
maximum stop input count rate	- 30×10^6 counts/sec.
threshold of input signals (start and stop) - 250 mV.	

The instrument was provided with a 5-position switch for 15 time range choices; 0.05, 0.1, 0.2, 0.4 or 0.8 μ s multiplied by X1, X10 or X100. It was also provided with an 8-position output amplitude switch for full range of 3 V to 10 V in 1.0 V steps.

The output of the TAC was constantly monitored with a Tektronix 7704 double trace oscilloscope and simultaneously recorded by a pulse height analyzer (PHA) during several minutes of operation. The PHA used throughout this work was a Northern type NS600, 256 channel analyzer. It had a digital zero-offset facility which increased its resolution to that of a 2048 channel instrument. This facility was extremely useful for measuring noise, diffusion spreading and the very short time intervals between successive drift distances.

Digital printout from the PHA was by means of a Teletype, 33 serial teleprinter. This instrument had a facility of storing the data in a

punched paper tape form. In this form it was possible to analyze the data by computer.

Another facility associated also with the PHA was a Hewlett Packard type 7040 X-Y plotter which was used to supply the data stored in the PHA in a graphical form.

When the system was used in the coincidence mode a pulse height discriminator had to be used. This unit was connected between the output of the linear amplifier and the 'COINC' input of the PHA. The discriminator used was an ORTEC, N1M unit model 406A single channel analyzer (SCA) (see Fig. 4.6). The lower level was set at zero and the upper level could be adjusted in the range 0 to 10 V. In some measurements pulse heights exceeded the upper limit, thus a divider (÷2) had to be used to bring these pulses within the limits of the discriminator.

4.3.6 Optimisation and calibration electronics

The complete electronic system used for drift velocity and longitudinal diffusion measurements consisted, in addition to the main setup described above and shown in Figure 4.6, of two subsidiary systems, a time calibration system and a test system for determination of the optimum conditions for measurements. Incorporation of the calibration and test systems in the main set-up made it convenient to check, from time to time, the performance of the electronics, i.e. long term stability, fluctuation in time calibration, and noise level. For the sake of simplicity, the calibration and test systems are presented here in a separate block diagram (Figure 4.14).

The system was accurately calibrated in time, in the following manner. Referring to Figure 4.14, a conveniently delayed pulse is derived from the master pulse generator (main output) and applied as a

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.



Fig. 4.14 Test and calibration electronics.

i

large value charge pulse to the 'TEST' input of the charge sensitive preamplifier. The time interval between the start and stop pulses to the TAC is then measured with a digital timer/frequency meter.

The 'DELAY' unit used here was another Venner TSA 628 pulse generator (see section 4.3.1). It was triggered externally and only the 'DELAY' control was varied for time calibration, i.e. the unit was used as a delay generator.

The digital timer/frequency meter (DFM) was a Venner model 7737A which was provided with an internal 10 MHz crystal oscillator. To achieve high degree of accuracy in time calibration it was necessary to employ an oscillator with higher frequency. An external 100 MHz oscillator (i.e. 10 ns period) was used. The DFM was first used to measure the frequency of the external oscillator. The instrument was then switched into the 'COUNT' mode for which it was provided with a gating circuit that could be operated by 'start' and 'stop' controlled signals. Therefore by feeding the start and stop signals from the calibration system to the corresponding inputs of the DFM (see Figure 4.14) it was possible to determine the delay of the stop signal with respect to the start in a form of a digital display (e.g. a count of 100 is equivalent to 1.0 µs delay). Hence in this way the 'DELAY' unit could be calibrated. The second step was to calibrate the time-offlight logic, i.e. the TAC and the PHA. For this matter the start and stop signals were fed into the corresponding inputs of the TAC whose output was connected to the PHA. Hence by varying the delay (its value could be read directly from the DFM), over a suitable time range, the peak channels of the distributions corresponding to the delay settings were determined from the PHA. The distributions stored in the PHA were, then, recorded in a form of a punched paper tape for computer

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analysis. The computer (Cyber 72) determined the position of each peak to the nearest 0.01 of a channel ($\simeq 0.1$ ns). The channel width (i.e. the time interval per channel), was then very accurately determined by computer (PDP11) employing a least square data fitting procedure. This calibration procedure was carried out for all TAC time 'RANGE's' and 'AMPLITUDE's', and PHA conversion gains of interest.

Optimisation of the electronics, e.g. determining the threshold of the crossover detector was achieved with the same system (Figure 4.14) with the DFM and oscillator switched off. A charge pulse from the proportional counter was simulated by a pulse applied to the 'TEST' input of the preamplifier. The height of this pulse was controlled by a Wyne Kerr type Q521 attenuator. The simulated input charge was determined from the product of the pulse height V_o and the calibration capacitance of the preamplifier, C_T. The true pulse height V_o was determined by matching the pulse of the test circuit (as observed on the oscilloscope) with a pulse from a precision pulse generator. The equivalent pulse height was read directly from the generator's dial.

4.4 Electronics for the lateral diffusion measurement

To date almost all systems that have been used to measure lateral diffusion coefficients by the Townsend type of apparatus, have employed current measuring equipment based on the double integrating balance set forth by Townsend in 1914 (see section 3.3.1). The availability nowadays of low noise performance operational amplifiers and their use in conjunction with a phase sensitive detector (PSD) makes it possible to employ an alternative current measuring system which is simpler and less costly than the double integrating induction balance, and is capable of measuring currents down to about 10^{-15} A.

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The basic principle of the method may be explained by referring to figure 4.15 which shows a schematic diagram of the diffusion chamber and the current measuring circuit. A CW U.V. source is used to initiate electrons from the cathode C. These are drawn to the source hole S by a square wave of a suitable frequency and amplitude. The square wave is simultaneously fed into the reference input of the phase sensitive detector PSD. The electrons then enter the diffusion chamber through the hole S drifting and diffusing towards the receiving electrode, in a uniform field established, throughout the cylindrical volume, by the field shaping electrode assembly. The experiment then consists in determining the current distribution at the anode by measuring the current i_b and i_q received at the central collector and the quadrants respectively. In such an experiment the magnitudes of currents involved are very small ($\sim 10^{-13}$ A). Under these conditions an operational amplifier with a very large feedback resistor (~2×10⁹ ohms) yields output voltages of the order 0.2 mV. We are interested in the ratio of the current received at the central collector to the total current $\left(\frac{\mathrm{i}_{\mathbf{b}}}{\mathrm{i}_{\mathbf{b}}+\mathrm{i}_{\mathbf{q}}}\right)$. received by the whole anode, i.e.

This ratio may be conveniently measured by the system shown in figure 4.15. The large value feedback resistor R_1 is connected to a precision potentiometer on the output of amplifier A_1 ; the large value resistor R_2 is connected to the junction of two equal resistors placed on the output of A_2 . If a potentiometer fraction r is required to make the two amplifier outputs equal (as detected by the differential inputs of the phase-sensitive detector), then

$$\frac{\mathbf{i}_{\mathbf{b}} \mathbf{R}_{1}}{\mathbf{r}} = \frac{\mathbf{i}_{\mathbf{q}} \mathbf{R}_{2}}{0.5}$$

In the present system the two high resistors were very closely matched,



Fig. 4.15 Electronic system for measurement of $D/\mu.$

 $R_1 = R_2$, so that

$$\frac{\mathbf{i}_{\mathbf{b}}}{\mathbf{i}_{\mathbf{q}}} = 2\mathbf{r} \quad \text{or} \quad \frac{\mathbf{i}_{\mathbf{b}}}{\mathbf{i}_{\mathbf{b}} + \mathbf{i}_{\mathbf{q}}} = \frac{1}{1 + \frac{1}{2}\mathbf{r}}$$

Therefore, current ratios are determined, simply, from the potentiometer setting.

In this set-up balance is achieved with the PSD. This device is an extremely useful tool in circumstances involving the detection of small currents in the presence of relatively large noise levels.

The electron current generated at the cathode is modulated by the square wave which simultaneously serves as a reference for the PSD. Modulation produces a component at the reference frequency with amplitude proportional to the main signal. The PSD produces a dc output proportional to the input signal which is always coherent with the reference signal. By choosing a suitable time constant, T, compatible with the experimental conditions, the dc output of the PSD is filtered to restrict the bandwidth and hence the noise. The effective noise bandwidth is given by (see Appendix II), $\frac{1}{4T}$. Thus for T = 3.0 s, the effective noise bandwidth is of the order 0.08 Hz.

Clearly the current measuring system described above have several advantages on the conventional double integrating induction balance system. In addition to its relatively lower cost and simplicity, this system greatly minimizes the broadband noise effects. Its stability is governed by the choice of suitable experimental parameter, e.g. the modulation frequency. It is virtually free from long term drift, (detailed analysis of noise performance, stability and choice of modulation frequency is given in Appendix II).

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4.4.1 The current amplifiers

The basic principle of the current amplifiers associated with the lateral diffusion apparatus is also discussed in appendix II. In this section the circuits of the two amplifiers used in this work, will be discussed. With the exception of the gain control components the two amplifiers were built up of identical (within the manufacturers tolerances) components. Figure 4.16 shows the detailed circuit. The operational amplifiers employed were PMI type OP-15G. Choice of these operational amplifiers was determined by their low noise performance, high signal gain, large input resistance and large gain bandwidth product. The manufacturers quote the following characteristics:

> Input noise current density - $0.01 \text{ pA}/\sqrt{\text{Hz}}$ Input impedence - $10^{12} \Omega$ Signal voltage gain - 200 V/mVGain bandwidth product - 5.4 MHz

The feedback resistors were high value $(2 \times 10^9 \ \Omega \pm 10\%)$ glass enclosed carbon megistors. DC gain measurements indicated that their values were in agreement to better than 0.7 per cent. The output of the amplifier A₁ was controlled by a 10 K Ω precision helipot potentiometer. The two resistors, R in the amplifier A₂ were matched to better than 0.1%.

Because of the small magnitudes of the currents measured and the very high input impedence of the amplifiers, precautions had to be taken against electrical pick-up, and stray leakage currents. The two amplifiers were enclosed in a well shielded cavity below the base plate of the diffusion chamber. The power supply pins of the operational amplifiers were decoupled to prevent interaction between the two amplifiers. The central collector and the quadrants were connected to

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the inputs of the amplifiers, <u>via</u> the glass-to-metal seals, by short screened leads. All measurements were carried out in a screened room.

4.4.2 The phase-sensitive detector

The unit used was an ORTEC Brookdeal type 9501E 'Lock-in Amplifier'. The characteristics of interest, as quoted by the manufacturers, are:

sensitivity	-	1 µV
frequency range	-	2 Hz to 100 KHz
output stability	_	100 ppm/°C
common mode rejection	-	100 dB
input noise voltage	-	10 nV rms/ \sqrt{Hz}

The instrument was provided with time constants range 1 ms to 30 s (ten settings). It could be used in a single mode as a voltage measuring instrument (A-mode) or in a differential, (A-B) mode for comparison purposes.

4.4.3 Square wave generator and UV-source

A Farnell type LFM-2 square-wave generator was used in the lateral diffusion system. Its frequency range was 1 Hz to 100 KHz. The maximum output amplitude was 12 V p-p.

The UV source employed was a Hanovia type 501/1 125 W mercury lamp.

4.5 The gases studied

The investigation carried out in this work covered a range counting gases. Three mixtures of methane in argon Ar/10% CH₄, Ar/50% CH₄ and Ar/75% CH₄ in addition to 100% CH₄ were studied. A range of mixtures of CO_2 in Ar was also studied. This range covered Ar/3% CO_2 , Ar/5% CO_2

and Ar/10% CO_2 . Finally one mixture of CH_4 in Ne was studied, that is Ne/10% CH_4 . All these gases were of the c.p. (chemically pure) grade. The suppliers quote the following typical purities of the gas components used:

gas component	typical purity (%)	<u>largest impurity</u> component present
Argon	99.999	moisture (2 vpm)
Methane	99.200	nitrogen (0.7%)
Neon	99.995	helium (<5 vpm)
Carbon dioxide	99.999	nitrogen (2 vpm)

For a two component gas the suppliers quote (a general rule for mixtures) an accuracy of $\pm 5\%$ in the smaller proportion component with the larger component being the balance. Therefore the largest margin of absolute error in the proportions (occurs in a 50%/50% mixture), is $\pm 2.5\%$.

CHAPTER 5

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EXPERIMENTAL METHODS AND PROCEDURES

5.1 Introduction

The principles of the time-of-flight and lateral diffusion methods were discussed in general terms in preceding chapters. In the present work the principles of these methods were adapted to apply to the experimental apparatus used.

The final forms of the time-of-flight and the Townsends type of apparatus that were adopted in the present work were described in detail in the preceding chapter. The initial design of the time-offlight apparatus was very similar to that of the ORNL group. It was originally intended to employ this apparatus to measure both drift velocity and longitudinal diffusion. The desire to measure longitudinal diffusion coefficients, in particular, initiated a series of experimental investigations, the outcome of which was a number of modifications to initial design of the time-of-flight apparatus.

In this chapter the principles of the methods and the experimental procedures used in the present work to measure or attempt measuring various transport coefficients will be discussed in detail. The modifications to the initial T.O.F. apparatus, made in an attempt to measure longitudinal diffusion coefficients, will be described and the results will be analyzed.

5.2 Principle of the Time-of-Flight Method

The basic theory of the T.O.F. method, as outlined by Hurst et al. (1963), was discussed in section 1.2.3. These authors have obtained expressions for the drift velocity w (equation 1.5), and the longitudinal diffusion coefficient D_{L} (equation 1.7), of the forms

$$W = \frac{d}{t_m} (1-\beta)$$

and

$$D_{L} = \frac{d^{2}\delta t^{2}}{4t_{m}^{3}} (1-2\beta)$$

where d, is the drift length; t_m , time at which maximum count occurs; δt , width of the distribution at $\frac{1}{e}$ maximum and β is a correction factor $=\left(\frac{D_L}{dW}\right)$.

5.2.1 Principle of the drift velocity method

The method applied by the ORNL group to determine the drift velocity, W, depended upon finding an approximate value of this parameter from the simple relation $W = \frac{d}{t_m}$. Then a more accurate value was determined by using a correction procedure applicable to their system (section 3.2.2). Although the basic method used in the present work to determine W was the same as that of the ORNL group, there were some differences in the analysis of the results. Unlike the ORNL method which was based on timing the motion of electrons over fixed drift lengths, the present method employed a variable drift length. As concluded in preceding chapters, this feature enabled first order end effects to be eliminated and hence it was possible to evaluate W, simply from the ratio of differences between drift lengths (Δx) to the differences in drift times (Δt_m), i.e.

$$W = \underline{\Delta \mathbf{x}}_{\underline{\Delta \mathbf{t}}_{\mathbf{m}}}$$

In the present time-of-flight apparatus Δx was determined with sufficient accuracy (±0.002 mm). The accuracy of Δt_m , on the other hand, was governed mainly by the stability of the electronics, the accuracy of the time calibration, and in particular by the accuracy in determining the position of the peak of the distribution corresponding to t_m . Calibration of the system was carried out with high degree of precision using the procedure described in section 4.3.6. It was checked from time to time and was found to vary little or none at all. Computer analysis of the calibration data indicated that the system was nearly linear (±0.1%). [Appendix IIIA shows a typical computer analysis of a set of calibration data. The data is presented graphically in figure 5.1.] It was necessary, therefore, to devise a procedure to determine t_m with a high degree of accuracy. A computer programme was written to analyse the time-of-flight distributions. The peak of a distribution was determined using the expression

peak channel =
$$\frac{\begin{matrix} i=N \\ \sum \\ 3 \\ i=N \\ \sum \\ 3 \\ n_i \end{matrix}$$

where n_1 is the number of counts recorded in channel c_1 and N_1 is the number of PHA channels employed (the same procedure was used to analyse the calibration data). To account for any skewness in the distributions or poor definition of peaks, the programme was devised to carry out the analysis above thresholds set, on the distribution being analyzed, at 0.1, 0.35, 0.6 and 0.8. Then above each of these thresholds a peak and the associated error were found. An extrapolated peak was finally determined for the distribution as a whole. A typical computer analysis is presented in Appendix IIIB. The procedure is illustrated graphically in figure 5.2.

The drift velocities corresponding to various E/p values were determined by a least-squares fitting procedure using the programme



Fig. 5.1 Typical time calibration graph.



Fig. 5.2 Graphical representation of computer analysis for a time-of-flight distribution.

presented in Appendix IIIA. A single velocity value was determined from a set of data points (normally five) i.e. the drift distances employed and the extrapolated peaks of the corresponding distributions. Analysis of data yielded the slope of the line passing through the data points, $\left(\equiv \frac{\Delta t_m}{\Delta x}\right)$, an intercept with the t_m axis (equivalent to an intrinsic delay of the system), and the errors in these two parameters. A typical set of results for one velocity value is presented in table 5.1 (the graphical representation of the data points is similar to figure 5.1 with the drift distances on the x-axis).

5.2.2 Experimental Procedure

A typical experimental procedure for drift velocity measurement was as follows.

Before starting the measurement the chamber was evacuated using a rotary pump. Baking of the chamber was not possible, therefore long periods (about 2 hours) of pumping were necessary to ensure the removal of traces of impurities resulting, for example, from outgassing. This procedure had to be repeated for each of the gases studied. For runs that were not completed on the same day, shorter periods of pumping were made before resuming the measurements. For measurements carried out at atmospheric pressure, however, this was not necessary because the gas was flown continuously.

UV pulses produced at a rate of 160 flash per second were used in most measurements. Sometimes, however, the repetition rate had to be altered to conform with the counting efficiency, C/F criterion, (Hurst 1963). The cathode pulse was adjusted to coincide with the maximum intensity of the UV-flash. This was achieved by adjusting the delay control of the master pulse generator until a maximum count rate was

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A typical set of data points fitted by a least-squares procedure using a PDP11 computer. Measurements were carried out in Argon/10% Methane at E/p = 0.2 V cm⁻¹ torr⁻¹. PHA, zero-offset = 256; channel width = 7.69 ns.

TABLE 5.1

Equivalent time tm (µs)	, , , , , , , , , , , , , , , , , , ,		2.334	2.415	2.508	2.603	
Extrapolated peak ** channel number (-256)	ZE 01	20.05	47.51	58.09	70.12	82.51	
Estimated peak * channel number (-256)	ZE E	c.cc	47.5	58.0	70.0	82.5	
Drift length x (cm)		0.2	2.5	3.0	3.5	4.0	

Computer analysis yielded:

Number of channels per cm = 23.19 Equivalent $\frac{\Delta t_m}{\Delta x} = \left(\frac{1}{W}\right)$ = 0.178 µs cm⁻¹ * These values were determined visually from the PHA display.

Equivalent intrinsic delay of the electronics = $1.886 \ \mu s$

Intercept with the t-axis at channel number = 245.24

** These values were determined by a Cyber 72 computer.



Fig. 5.3 Schematic diagram illustrating application of drift voltage.

reached. The maximum count rate was determined by a scalar-counter or visually from the signal monitored on the oscilloscope. The cathode pulse width and the cathode/grid bias were then adjusted at optimum settings. Optimum settings of these units, together with the repetition rate, were determined by the counting efficiency required. C/F values ranging from 0.1 to 0.2 were used throughout this work.

For drift lengths adjustments, the micrometer had been calibrated prior to the measurements by setting the grid of the photocathode assembly in the plane of the topmost field shaping ring (drift length = 5.0 cm), and recording its reading. [The movement of the photocathode head was observed through the glass window on the side of the housing.] Then the next drift position down was the initial micrometer reading minus 5.0 mm and so on. All positions, as set by the micrometer, were checked and in each case the grid was found to be coplanar with the corresponding ring.

In operation the drift length was set by adjusting the photocathode head in the required position (say, the "5.0 cm" position). Then the drift voltage (supplied by a Brandenburg unit model 412R, 2 KV and measured with a Solartron type 7040 digital voltmeter with an accuracy of 0.1%) was applied. This voltage which corresponded to the drift field desired, was fed simultaneously to the '5.0 cm' ring through the PET connector corresponding to that position, and to the photocathode assembly through the biasing network (figure 5.3). The performance of the system was monitored on a double-trace oscilloscope displaying the outputs of the linear amplifier and the TAC. If found satisfactory the time-of-flight distribution would be recorded in the PHA for periods of operation ranging from 10 to 20 minutes. The drift length was then set at the next position down i.e. (4.5 cm). The drift voltage supply was

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connected to the PET connector corresponding to this position. The voltage was adjusted to provide a drift field equal to the preceding value. The time-of-flight distribution for this position was then recorded in a fresh PHA memory. This procedure could be repeated for the next five positions thus providing seven time-of-flight distributions from which a single drift velocity value could be obtained as a function of a particular E/p value. However, it was found that, in most cases, five positions only were quite sufficient to provide adequate accuracy.

The time-of-flight distributions recorded in the PHA were then stored in a paper tape punched by the teleprinter. The data was then analyzed by computer using the procedure described in the preceding section. Figure 5.4 shows a typical set of distributions recorded with an X-Y plotter.

5.3 Methods and procedures for longitudinal diffusion measurements

We have seen in section 5.2.1 that with the present system drift velocity values could be obtained from a straightforward space-time relationship without the need for the correction factors applied by the ORNL group. However, interpretation of the arrival time distributions, obtained in the present work, for the evaluation of longitudinal diffusion coefficients was rather difficult. A long series of experiments was carried out in an attempt to evaluate this parameter as a function of E/p in some counting gases. Three methods of measurements and interpretation of data were attempted. The first method was based on the original interpretation of Hurst <u>et al</u>. (1963 and 1966) and using a similar system. The second method employed a substantially reduced electron pulse thereby reducing the contribution to the arrival

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time spectra by the UV pulse. The third method depended upon overlapping two distributions from two drift lengths of a known separation. The time-of-flight theory (Hurst <u>et al</u>. 1963) was used here but the results were analyzed differently.

5.3.1 The ORNL method

In the first method attempted a system closely resembling that of Hurst <u>et al</u>. (1963) was used. It consisted of a swarm chamber and an electronic system (figure 5.5). The chamber was essentially as described in section 4.2.1 with the following differences. The photocathode head was used without employing a grid, i.e. the photocathode disc represented the top boundary of the drift space. The other boundary was the aperture disc. A circular aperture of 1.0 mm diameter was used through which electrons entered the proportional counter. With this configuration the principle requirement upon which the theory of the method was based (i.e. an extended electron source and a point detector), was approximately satisfied.

The electronic system with the exception of the start channel, was the same as that described in section 4.3.1. In operation electrons were generated by back UV irradiation in the manner described in section 4.2.1. Pulses of UV light were produced at a rate of 160 flashes per second by an E.G&G xenon filled flash tube and monitored by an E.G&G photodiode type SD100 (both the flash tube and the photodiode were of the same types used by the ORNL group). The photodiode measured pulses of amplitude, 2 V and duration ~625 ns. The pulse monitored by the photodiode served to trigger the start of the TAC for the time-of-flight measurements. The stop pulse was produced by the detection of a single electron by the proportional counter. The

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Fig. 5.5 Electronic system employed in measurement of DL using the ORNL method.

counting efficiency, C/F was adjusted at about 0.1.

Preliminary results with this arrangement indicated that the spread of the distribution was dependent, as expected, on the pressure. At atmospheric pressure the full width at half maximum (FWHM), measured for Ar/10% CH₄ at E/p, 0.2 V cm⁻¹ torr⁻¹, amounted to about 735 ns. Obviously the largest portion of this was contributed by the UV pulse width (625 ns). The measured electronic noise contribution was ~30 ns. An approximate calculation was carried out to estimate the contribution to the spread by diffusion (Δ t)₄ using the equation,

$$\sigma \simeq \sqrt{2D t} = \sqrt{2D \frac{d}{w}}$$
,

where σ is the standard deviation. The value of D, chosen (from theoretical calculations of lateral diffusion) was $\sim 10^{-2}$ cm² µs⁻¹. The drift length, d, over which the measurement was carried out was 5.0 cm. Measured drift velocity (w) value at E/p = 0.2, was ~ 5.6 cm² µs⁻¹. With these values the contribution to the spread by diffusion amounted to ~ 60 ns (FWHM) clearly the combined effect of the pulse width and electronic noise was substantially greater than that of diffusion. Therefore application of the deconvolution analysis adopted by Hurst <u>et</u> <u>al</u>. (1963 and 1966) to extract (Δt)_L from the overall distribution width would have been rather difficult and unjustified.

Comparing the experimental conditions of the present work with those of the ORNL group, one can see the following:

[1] The UV pulse width claimed to have been measured by the ORNL group was 275 ns at $\frac{1}{e}$ peak amplitude (Wagner <u>et al</u>. 1967). This is contrary to the values specified by the manufacturers of the flash tube who quote durations (depending upon the value of the discharge capacitor) ranging from 0.5 to 15 µs at $\frac{1}{3}$ peak amplitude.

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[2] In the measurements carried out by the ORNL group, pressures ranging from 1 to 25 torr were used. In the present work, experience showed that to control the pressure in such a range while maintaining continuous gas flow was rather difficult.

[3] The time-of-flight chamber employed by the ORNL group had a drift length, 25 cm, whereas the maximum drift length used in the present work was 5.0 cm.

Therefore with the system described above limited by the UV pulse duration, pressure and drift length, determination of longitudinal diffusion coefficients was not feasible. To improve the performance of the system two possibilities were considered. Firstly, the contribution by diffusion to the arrival time distribution may be enhanced by employing a much longer drift distance. Secondly, the contribution by UV light pulse may be substantially reduced resulting in a distribution in which the contribution by D_L dominates. From a practical viewpoint the second possibility seemed more favourable and attractive.

5.3.2 D_L Measurements using pulses of shorter duration

The search for an alternative technique that would yield narrower pulses opened two options for consideration. The first option was to attempt to design and build a fast flash lamp of the types suggested by Bredford (1970) or Caceres et al. (1974). These authors designed, constructed and tested, independently, UV flash lamps which were claimed (in both works) to provide pulses of duration, 15 ns. Preliminary investigations indicated that to achieve such narrow durations would be at the expense of the light intensity. Calculations showed that production of adequate intensity to operate the present system would

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lead to pulses of duration comparable with that of the flash used in the first longitudinal diffusion measurement attempt (section 5.3.1). For this reason this option was abandoned.

The second option considered was to superimpose a narrow electronic pulse on the UV flash to control injection of electron into the drift region for very short durations. Although adoption of this option required major modifications to be carried out on the system, it was more favourable than the first one for its compatibility with the apparatus and the requirements of longitudinal diffusion measurements. Modifying the system described in section 5.3.1 required re-designing the photocathode head to include a grid below the photocathode disc for controlling the transmission of electron pulses into the drift region. The modified form of the photocathode head was described in section In order not to violate the basic principle upon which the 4.2.1. theory of this method depended (i.e. extended electron source and point detector), a flat gold coated stainless steel circular grid of a diameter, 35 mm, aperture, 0.1 mm and optical transmission 50%, was used instead of the 6.0 mm diameter micromesh grid described in section 4.2.1. With this arrangement it was necessary to pulse the cathode using pulses of durations compatible with the gases being studied. A cathode pulser capable of providing pulses of durations ranging from 20 to 120 ns, was constructed (section 4.3.3). The cathode-grid configuration, also required a DC biasing voltage to prevent passage of electron swarms during the absence of the control pulse.

With these modifications it was possible to reduce the contribution to the arrival time spectrum by the pulse width substantially. However, introduction of the grid into the system produced a serious complication in the analysis of data. Consider, the three factors contributing

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to the spread of a spectrum discussed in section 3.3.2 i.e. electronic noise, UV pulse width and diffusion. The total spread σ may be expressed as,

$$\sigma_{\mathrm{T}}^2 = \sigma_{\mathrm{n}}^2 + \sigma_{\mathrm{T}}^2 + \sigma_{\mathrm{L}}^2 \tag{5.1}$$

where σ_n^2 , σ_τ^2 and σ_L^2 are the contributions of noise, pulse width and longitudinal diffusion respectively. For the present system σ_L has two components representing the contributions by diffusion in the drift region, σ_D^2 and in the proportional counter, σ_c^2 . The presence of the grid in this method introduces an additional contribution to the spread. The time variation due to electrons, of different swarms, travelling through the grid along different paths has to be taken into account. In this case equation 5.1 may be written as

$$\sigma_{\tau}^2 = \sigma_{\mathbf{n}}^2 + \sigma_{\tau}^2 + (\sigma_{\mathbf{p}}^2 + \sigma_{\mathbf{c}}^2)_{\mathbf{L}} + \sigma_{\mathbf{d}}^2$$
(5.2)

where σ_{d}^{2} is the contribution by electron path variation.

Various attempts were made to evaluate longitudinal diffusion from data obtained with the modified apparatus in conjunction with the electronics shown in figure 4.6. In these attempts two variables were exploited, i.e. drift length and gas pressure, in detecting the effect of longitudinal diffusion. Drift lengths ranging from 2.0 cm to 4.0 in steps of 0.5 cm, and pressures ranging from 50 torr to atmospheric, were used. In operation the counting efficiency C/F was always kept at about 0.1. The electronic system was nearly linear (±0.1%). The timeof-flight data was punched in paper tape and analysed by a Cyber 72 computer in the manner described in section 5.2.1. The analysed data yielded, in addition to the peak of the distribution, its FWHM and width at $\frac{1}{e}$ peak (Appendix IIIB). A typical set of data of spectrum

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FWHM versus drift length is shown in table 5.3. In each case the corresponding full width at $\frac{1}{e}$ maximum is also shown. The results were obtained under the following conditions:

```
gas - a mixture of argon/10% methane,

pressure - atmospheric,

flow rate - 50 cc per min.,

E/p - constant for all drift positions

(= 0.2 V cm<sup>-1</sup> torr<sup>-1</sup>),

anode voltage - 2.1 KV,

cathode pulse width, \tau - 62 ns,

cathode-grid bias V<sub>CG</sub> - 2.7 V,

PHA channel width - 7.69 ns.
```

TABLE 5.3

Experimentally determined FWHM and width at 1/e peak as a function of drift length, x, at a constant E/p, for A/10% CH₄.

x (cm)	FWHM (ns)	width at ¹ /e max. (ns)
2.0	53.45	64.60
2.5	53.98	65.21
3.0	54.98	66.13
3.5	58.91	71.82
4.0	60.44	74.29

To assess the possibility of evaluating longitudinal diffusion coefficients, attempts were made to interpret data, obtained with the system configuration described above, using equation 5.2. Approximate values for $(\sigma_{\tau})^2$, as a function of drift length, were calculated by evaluating the individual components contributing to the total spread.

These were evaluated in the following manner:

(a) <u>Electronic noise contribution</u> (σ_n^2) :

The contribution by electronic noise was measured accurately using the test electronics (figure 4.13). It was also calculated (section 6.5.1). The two values were found to be in satisfactory agreement. The value obtained by measurement was

 $(FWHM)_{noise} = 30 \text{ ns}$

Therefore $\sigma_n^2 = \left(\frac{30}{2.35}\right)^2 \simeq 163 \text{ ns}^2$

(b) The effective pulse width contribution (σ_{τ}^2) :

The value of σ_{τ}^2 was estimated using the argument of section 4.3.3, i.e.

 $(FWHM)_{T}$ = (cathode pulse width) - (cathode-grid transit time)

The time required by an electron to traverse the cathode-grid region, (2.0 mm), was determined from the drift velocity corresponding to the E/p value in that region. Since the cathode pulse height was 40 V, then E was 200 V cm⁻¹, and at atmospheric pressure E/p was ~0.26. At this E/p value the drift velocity measured in the present work was ~5.4 cm μ s⁻¹. Therefore the cathode-grid transit time was ~37 ns, and the effective pulse width,

and

$$(\text{FWHM})_{\tau} \simeq \tau - 37 \simeq 25 \text{ ns}$$

 $\sigma_{\tau}^2 \simeq \left(\frac{25}{2.35}\right)^2 \simeq 113 \text{ ns}^2$

(TT. T D C)

(c) <u>Contribution due to electron path variation</u>, $(\sigma_d)^2$:

This contribution was difficult to quantify. It was assumed that it had a small fixed magnitude.

(d) <u>Contribution by diffusion in the proportional counter</u>, (σ_c^2) : The value, σ_c^2 was estimated using the classical formula,

$$\sigma^2 = 2 \text{ Dt} = 2D \frac{d}{W} \text{ cm}^2$$
, (5.3)

where D is the diffusion coefficient, and t, d and W are the drift, time, length and velocity respectively. To determine D and W in the counter, the E/p value had to be established first. The electric field E_a at the aperture due to the anode voltage V_a is given by

$$E_a \simeq 0.2 V$$
 (section 4.2.3)
= 420 V cm⁻¹,

and at atmospheric pressure $E/p \sim 0.55 \text{ V cm}^{-1} \text{ torr}^{-1}$. Then at $E/p = 0.55 \text{ V cm}^{-1} \text{ torr}^{-1}$ the drift velocity value measured in the present work for A/10% CH, was ~4.0 cm µs⁻¹. For D, since there was no longi-tudinal diffusion data available for the gas, its value was chosen from theoretical calculations of isotropic diffusion carried out in the course of this work. At $E/p = 0.55 \text{ V cm}^{-1} \text{ torr}^{-1}$, the value of D chosen was ~7.3 ×10⁻³ cm² µs⁻¹. The value of t, was approximately found from the ratio of drift length to drift velocity. The drift length, i.e. the distance between the anode wire and the aperture was ~1.5 cm. Putting these values into equation 5.3 yielded,

 $\sigma_c^2 \simeq 340 \text{ ns}^2$

(e) <u>Contribution by diffusion in the drift region</u>, (σ_p^2) : The same method of calculation, used under heading (d), i.e. employing equation 5.3, was applied here to estimate the contribution due to diffusion in the drift region as a function of drift length. The values of D and W, corresponding to $E/p = 0.2 V \text{ cm}^{-1} \text{ torr}^{-1}$, used here were, respectively, $9 \times 10^{-3} \text{ cm}^2 \mu \text{s}^{-1}$ (from theoretical calculations) and 5.6 cm μs^{-1} (measured). The calculated σ_p^2 value corresponding to various drift lengths was added, in turn, to the sum of σ_n^2 , σ_T^2 and σ_c^2 (this sum was assumed constant = 616 ns²) yielding the estimated total spread $(\sigma_T^2)_E$ as a function of drift length. These results are presented in table 5.4. Shown, also, in table 5.4 are the corresponding values measured with the present system configuration, $(\sigma_T^2)_M$. The $(\sigma_T^2)_M$ values were determined from the FWHM results presented in table 5.3.

TABLE 5.4

drift length (cm)	$(\sigma_{T}^{2})_{E}$ (ns ²)	$(\sigma_{\tau}^2)_{M}$ (ns ²)
2.0	821	517
2.5	872	528
3.0	923	547
3.5	984	628
4.0	1025	661

Estimated $(\sigma_T^2)_E$, and measured $(\sigma_T^2)_M$ as a function of drift length

These $(\sigma_T^2)_E$ and $(\sigma_T^2)_M$ data are represented graphically in figure 5.6.

Examination of the data obtained by this method for a number of gases indicated the following:

[1] Although the major factor contributing to the arrival time



Fig. 5.6 Comparison between (σ_{τ}^2) measured and (σ_{τ}^2) estimated.

distribution spread, i.e. the UV pulse width, had been substantially reduced, the contributions by longitudinal diffusion obtained under the present conditions were still too small to be extracted from the spectra to yield reliable data. This effect can be seen clearly in figure 5.6.

[2] Longitudinal diffusion dependence on drift length was one method exploited to investigate the worthiness of the technique. Results obtained by this technique showed inconsistencies in FWHM intervals corresponding to drift length intervals (see, for example, table 5.3).

[3] On the assumption that the combined effect of all factors, other than $\sigma_{\rm D}$, contributing to the widths of distributions was constant, observations indicated dependence of these widths on the drift field. Broader spectra were obtained at drift fields corresponding to low drift velocity values and vice versa.

[4] Attempts to operate the system, in continuous gas flow mode, at low controllable pressures, i.e. to enhance the contribution to the spread, by diffusion, resulted in broader spectra than obtained at atmospheric pressure under the same (x and E/p) conditions. Nevertheless, even at these reduced pressures the dependence on drift length remained inconsistent. The effect of pressure on the arrival time distributions is shown in figure 5.7 displaying a set of spectra obtained under the following conditions:

> gas : A/75% CH₄ drift length : constant (= 4.0 cm) E/p : constant (= 0.4 V cm⁻¹ torr⁻¹) cathode pulse width: 40 ns cathode grid bias : 2.7 V



Fig. 5.7 Time-of-flight distributions obtained, at various pressures, under the same experimental conditions.

PHA channel width: 6.2 ns.

The variation of FWHM and full width at $\frac{1}{e}$ maximum with pressure, for this set is shown in table 5.5.

TABLE 5.5

Variation of FWHM and width at 1/e maximum with pressure

Pressure (torr)	FWHM ns	width at ¹ /e max. ns
50	119.35	142.35
100	86.61	101.06
200	64.23	77.31
300	63.05	74.77
500	50.10	67.21

One approach tried to interpret the data was based on applying the expression used by the ORNL group to determine approximately values of longitudinal diffusion coefficients D_{L} from experimental results. It was shown in section 1.3.2 (equation 1.7) that

$$D_{L} \simeq \frac{\delta t^{2} d^{2}}{4 t_{m}^{3}}$$
(5.4)

where δt and t_m are time values corresponding respectively to the full width at 1/e maximum and the peak of a distribution, and d, is the drift length.

Under ideal conditions a graph of δt versus d would yield a straight line, similar to that of figure 5.6, with the intercept with the δt axis representing the sum of the effects discussed under headings (a), (b), (c) and (d) above. It was hoped that by using this differencing procedure the combined effect, which was assumed constant under the same experimental conditions, would be eliminated. Then by finding &t (from the graph) and t_m (from drift velocity measurements), corresponding to diffusion and drift for d = 1 cm, and applying equation 5.4, D_L values could be obtained without the need for corrections. But, as discussed earlier, the inconsistencies and the magnitude of variations in δt differences were so large to the extent that D_L values seemed to be independent of drift field. The inconsistencies in the data, obtained with the differencing procedure under the same experimental conditions, appeared to be mainly associated with the variation in drift length. One line of investigation followed here to explain this effect laid stress on the factor discussed under the heading (c) above, i.e. the contribution to the spread by the variation of electron flight paths. It was believed that an unknown dependence had existed between σ_d and drift length. Therefore, the validity of the assumption that the combined contribution of σ_n^2 , σ_τ^2 , σ_c^2 and σ_d^2 , (obtained at the same E/p value and different drift lengths) is questionable. Hence application of the differencing procedure to data obtained from the system with its present configuration, was not appropriate.

Among the possible causes of the inconsistency, the effect of impurities on the results was considered. The level of impurities from outgassing and leakage, as measured in the present work, and the intrinsic gas impurities as quoted by the suppliers, (BOC), might have been partly responsible for the irregularities but did not explain the large variations observed.

For these reasons a different approach was tried to analyze the experimental results. This will be discussed in the following section.

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5.3.3 Experimental results analysis using two overlapping distributions

In the series of attempts to evaluate longitudinal diffusion coefficients one approach that was rather different from those discussed above, was considered. In developing the principle of this approach, as applied to the present systems, the basic time-of-flight theory was used. It depended on analyzing the data of two overlapping distributions recorded at two drift positions of a known separation. The theory of the method can be explained in the following.

An experimental distribution, (as a function of time t), such as those obtained in the present work, may be represented by the diagram shown in figure 5.8(a). In such a distribution there is an unknown constant time shift, t_0 due to instrumental delays. The true drift time t, is given by

$$t = t' - t_0$$
 (5.5)

Assuming that Poisson distortion and diffusion to the electrodes are negligibly small (i.e. $\frac{D}{Wd} \ll 1$), then the number of electrons, E(t) Δt arriving at the aperture of the proportional counter between t and t + Δt is given by (equation 1.3),

$$E(t)\Delta t = W a N_o (4\pi D_L t)^{-1_2} exp \left[- \frac{(d - Wt)^2}{4 D_L t}^2 \right]$$
 (5.6)

Here d is the drift length, a is the aperture area and N_0 is the initial electron intensity. Now, consider two overlapping distributions, (figure 5.8(b)), to be recorded from drift distances d₁ and d₂ under exactly the same experimental conditions, e.g. N_0 and E/p. Let these distributions be denoted by $E_1(t')\Delta t'$ and $E_2(t')\Delta t'$. Then by manipulation of equation 5.6 it can be shown that,

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$$y = (t'_{x} - t') \frac{(d_{2} - d_{1})/2}{\log[E_{1}(t')/E_{2}(t')]} = \frac{D}{W} t' - \frac{D}{W} t_{0}$$
(5.7)

and
$$W = \frac{1}{2} (d_2 + d_1) / (t'_x - t_o)$$
 (5.8)

where $t'_{\mathbf{x}}$ is the time corresponding to the intersection of the two distributions.

The quantity denoted by y in equation 5.7 may be calculated from the two spectra provided t'_x is accurately determined. Thus y can be plotted against t' to yield a straight line of slope D_L/W and an intercept on the time axis, t_0 (figure 5.8(c)). Since W can be calculated from equation 5.8, therefore D_L is determined from the slope of the line.

This method was tried using the system configuration described in the preceding section. The experimental procedure was similar to that described in section 5.2.2 with some additional steps as follows: The conversion gain of the PHA and the controls of the TAC were adjusted at suitable settings to allow the main bodies of the two spectra overlap. At the E/p value required, the counting efficiency, C/F, was adjusted at about 0.1. For the first drift position, d_1 , then, a distribution was recorded until the total count reached a certain value (say 10,000) monitored by the scalar counter. The second drift length, d_2 was then adjusted and its distribution was recorded, in another PHA memory, until the total count was the same as the previous value. The two sets of data were then printed out with the teleprinter and analyzed. Data analysis was carried out by hand in the following manner: The time t'_x , corresponding to the point of intersection of the two distributions (channel number in this case), was first determined. This was achieved by plotting the count n(C) versus the channel number, C, using the data

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Fig. 5.8 Diagrams illustrating the steps used in determining $D_{\rm L}$ by the method of overlapping distributions.

near the point of intersection. These data could approximately be represented by two intersecting straight lines as shown in figure 5.8 (d). Then from the graph, the channel number corresponding to t_x , was determined. Using equation 5.7, the values of y, corresponding to t', and E₁ and E₂, were found. Table 5.6 shows a typical set of results obtained for Ar/10% CH₄ using drift lengths 3.0 cm and 5.0 cm and E/p, 0.3 V cm⁻¹ torr⁻¹.

As mentioned above, the theory of this method depends upon accurate determination of t_x . It is also based on two main assumptions; firstly, it assumes that $\beta = \frac{D_L}{Wd} \ll 1.0$; and secondly, it assumes that the combined contribution, to the spectrum spread, by all factors other than diffusion, is constant.

From the practical and analytical viewpoints, the value of t'_x was determined with sufficient accuracy, (at least for the preliminary trial runs), using the method described earlier in this section. The assumption that $\beta = \frac{D_L}{Wd} \ll 1.0$, was approximately met by adjusting the experimental conditions such that C/F was ~0.1. However, the second assumption was violated because (as discussed in the preceding section), the sum of the contribution, to the spread, by all factors other than diffusion was not constant. With this limitation, therefore, the theory could not be applied successfully to the present system.

This method has a number of advantages; for example it utilizes an extended section of each spectrum in the data analysis rather than relying upon the peak readings. It can be used to determine, simultaneously, both W and D_L , from the time-of-flight distributions. It can, probably, be extended to cover more than two distributions. Although the length time involved in analyzing the data may be a disadvantage, this can be substantially reduced with the use of a suitable computer

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programme.

Application of this theory to the present time-of-flight apparatus was an attempt to examine its feasibility in determining longitudinal diffusion coefficients. Clearly further work is required to develop it both experimentally and theoretically. It is unfortunate because of time limitation this work could not be done during the course of the present studies.

<u>TABLE 5.6</u>

A typical set of results obtained with the two overlapping distributions method. The variation of y with n(c) ($\exists t_x'$) in Ar/10% CH₄. The channel number corresponding to t_x' was 72.85.

n(c) (≣t')	E1	E2	У
63	2197	230	4.34
64	2784	407	4.60
65	3542	652	4.64
66	3690	978	5.16
67	4102	1420	5.52
68	4241	1805	5.68
75	2227	4072	3.56
76	1685	3837	3.83
77	1237	3524	3.96
78	997	2966	4.72
79	802	2189	6.12
80	675	1732	6.59

5.4 Principle and procedure of the lateral diffusion measurement

In sections 4.2.4 and 5.5, the principle of the lateral diffusion measurement was outlined briefly. In this section the method, as applied to the present system will be discussed in more detail and the experimental procedure adopted will be described.

The basic expression used to evaluate the parameter D/μ was that of the current ratio R (equation 4.2), which reads

$$R = 1 - \frac{h}{d} e^{-\frac{W}{2D} \cdot \frac{b^2}{2h}}$$
(5.9)

Crompton and Jory (1962) suggest that the theory leading to equation 5.9 gives more consistent D/μ results than the other theories (these are discussed in detail in Huxley and Crompton 1974), for a Townsend-Huxley type of diffusion chamber. The ratio R may now be expressed in terms of the experimentally measurable parameter, r (the potentiometer reading).

$$R = \frac{\mathbf{i}_{\mathbf{b}}}{\mathbf{i}_{\mathbf{b}} + \mathbf{i}_{\mathbf{q}}}$$

where i_b and i_q , as before, are the currents received at the central collector and the quadrants respectively. Referring to figure 4.15, for $R_1 = R_2$ the balance condition is (equation 4.3)

$$\frac{i_{q}}{i_{b}} = \frac{1}{2r}$$

and $1-R = \frac{1}{1+2r}$ (5.10)

From equation 5.9 we may write, (provided $\frac{h}{d} \approx 1$)
$$\frac{1}{\log(1+2r)} = \frac{2D}{W} \left(\frac{2h}{b^2}\right)$$
(5.11)

Hence a graph of $1/\log(1 + 2r)$ versus h yields a straight line passing through the origin (provided that the system is accurately axially aligned; (see section 6.6.1), with a slope $S = 4D/Wb^2$. Thus a D/μ value corresponding to some E/p and a fixed pressure may be determined from the slope, S, of the line using the relation

$$\frac{D}{\mu} = S \cdot \frac{b^2}{4} (E/p) \cdot P$$
(5.12)

To cover the largest possible D/μ range, full advantage was taken of the current measuring equipment employed in the present work. The currents to the two portions of the receiving electrode were always measured so that the smaller current was obtained as a fraction of the larger. In the normal mode of operation described above one can see (equation 5.10) that as $r \rightarrow 0$, the current ratio $R \rightarrow 0$ and this occurs when $i_b \rightarrow 0$. On the other hand, as r approaches unity the ratio $R \rightarrow \frac{2}{3}$ and this occurs when $i_b \rightarrow 2i_q$. Therefore this mode covers a range of i_b from zero to $2i_q$. In another mode of operation used, extension of this range was achieved by interchanging the input leads to the two amplifiers such that the quadrants were connected to the circuit containing the potentiometer. In this mode the balance condition is

$$2i_b = \frac{i_q}{r}$$

and the expression corresponding to equation 5.10 is

$$1 - R = \frac{2r}{1 + 2r}$$
 (5.13)

In this case we can see that as $r \rightarrow 0$, R approaches unity, i.e. $i_q \rightarrow 0$,

and as r + 1, $R + \frac{1}{3}$, i.e. $i_q + 2i_b$. The expression corresponding to equation 5.11 is

$$\frac{1}{\log\left(1+\frac{1}{2r}\right)} = \frac{2D}{W} \left(\frac{2h}{b^2}\right)$$
(5.14)

A graph of $\left| \frac{1}{\log \left(1 + \frac{1}{2r}\right)} \right|$

versus h gives, as before, a straight line passing through the origin. In this case equation (5.12) is also applicable for the determination of the parameter D/μ .

The experimental procedure adopted for determining D/μ was as follows:

In deriving equations 5.10 and 5.13 it was assumed that the ratio $\frac{R_1}{R_2}$ of the feedback resistors is unity. In reality this was not exactly so. Therefore the first step in this set of measurements was to determine with sufficient accuracy this ratio. Determination of $\frac{R_1}{R_2}$ was achieved by finding the DC gain of the amplifier A₁ with the potentiometer set exactly at 0.5 and relating it to the gain of A₂.

Since the axial alignment of the system was of an utmost importance in the accuracy of the D/μ measurements, great care was taken to achieve this step with high degree of accuracy. (The effect of misalignment will be discussed in section 6.6.1). The preliminary alignment of the system was made using a gas mixture of A/10% CH₄ flown continuously at atmospheric pressure; (the same procedures for evacuating the system and flowing the gases described in section 5.2.2 in connection with drift velocity measurements, was applied in the D/μ measurements). The current amplifier of the central collector was connected to the input

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of the PSD. Using the A-mode of the PSD (section 4.4.2) and with all the units switched on, the response of the PSD meter to the current received at the central collector was observed. With the use of the alignment facility of the system (section 4.2.2), the PSD response was maximized along one of the axes. Then the same procedure was carried out along the other alignment axis (at right angles to the first). This procedure was repeated several times until the overall maximum response was found. Measurement procedure was then carried out. The PSD was switched to the differential mode (i.e. A-B-mode). With the diffusion length set at the required position and the drift voltage (corresponding to the E/p value desired) applied (this procedure was similar to that used in drift velocity measurements - section 5.2.2), a suitable PSD sensitivity was chosen.* Application of the drift voltage caused the pointer of the PSD meter to be deflected to one side of the central zero position. The balancing procedure was then carried out. The potentiometer of the amplifier A_1 was wound in such a direction to bring the PSD pointer to the central position of the meter. During this process the sensitivity of the PSD was increased gradually until near or at the null position the instrument had a sensitivity of 5 μ V. At the null position the pointer showed a random fluctuation about zero (the mean of these fluctuations had been set, prior to the measurement, such that it corresponded to the PSD dial zero; this was achieved using the zero off-set control of the instrument). The null position was checked by two means. Firstly, the phase was changed through 180° and the fluctuations were observed for several minutes. A

^{*} Since the PSD was very sensitive to transients, the instrument had to be set at very low sensitivity before applying the drift voltage.



second check was by matching the fluctuations at the null position with the random noise of the amplifiers. This check was carried out by stopping the UV light from reaching the exposed end of the light guide. These checks ensured accurate potentiometer settings. The balancing procedure was then repeated for a set of diffusion distances (at least three) using the same E/p value each time. [Figure 5.9 shows a typical set of results obtained for A/10% CH₄ at E/p = 0.2 V $cm^{-1} torr^{-1}$.]

CHAPTER 6

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PRELIMINARY INVESTIGATIONS

6.1 Introduction

It was concluded in the preceding chapter that the time-of-flight apparatus used in the present work was not suitable for measurement of longitudinal diffusion. Since the experimental attempts that led to this conclusion were discussed in section 5.3, this chapter will be devoted only to the preliminary investigations made on drift velocity and lateral diffusion coefficient. In order to achieve high degree of accuracy in the measurements of these parameters, a series of experimental and theoretical investigations had been carried out to study the influence of various effects, physical, geometrical and electronic, on the results. In this chapter therefore these effects will be discussed together with the problems encountered during the course of the work. It is convenient to divide the discussion into two parts to deal with drift velocity and lateral diffusion separately. However, there are some common factors between these two parts and these will be pointed out in relevant sections.

6.2 Influence of physical effects on drift velocity measurements

Among the physical effects the influence of temperature and pressure variations on the drift velocity results were investigated. The effect of temperature change was investigated theoretically whereas investigations of pressure changes were carried out experimentally.

6.2.1 Effect of temperature change on drift velocity results

From very elementary theory we may express the drift velocity, W,

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$$W \simeq \frac{1}{2} \frac{eE}{m} \frac{\lambda}{c}$$

where λ is the mean free path and c is the electron velocity for a single component gas. Here $\lambda = \frac{1}{\sigma N}$, where σ is the collision frequency and N is the molecular density. Since N = P/kT, we have

$$W = \left(\frac{E}{P}\right) \frac{ek}{2m\sigma} \frac{T}{c}$$

If we assume (incorrectly) that the electron mean velocity, c, is determined by the molecular thermal energy, that is

$$\frac{1}{2} m\bar{c}^2 = \frac{3}{2} kT \quad \text{or} \quad \bar{c} = \left(\frac{3kT}{m}\right)^{\frac{1}{2}}$$

then

$$W \sim \left(\frac{E}{P}\right) \frac{e}{2\sigma} \left(\frac{kT}{3m}\right)^{L_2}$$

Thus for constant pressure, $W \propto T^{\frac{1}{2}}$. Hence $\frac{dW}{W} = \frac{1}{2} \frac{dT}{T}$, or, at 300°K, $\frac{dW}{T} = \frac{dT}{600} = 0.17\%$ per degree.

A study of the full theory shows that to a first approximation the above result follows also. In more detail the effect is difficult to predict analytically. The effect of temperature change on drift velocity was determined by using different temperature values in the programme (Appendix I) employed in calculating transport coefficients. Calculations carried out for A/10% CH₄ at 273°K, 290°K and 300°K, indicated that $\frac{\Delta W}{W}$ does not exceed 0.2% per degree over the range of E/p of interest. A change, with temperature, of the same order seems to occur in D/μ (from calculations).

6.2.2 Effect of pressure on drift velocity measurements

We have seen (section 5.3.3) that the effect of reducing the pressure resulted, as expected, in broadening the time-of-flight distributions. This effect can be seen in figure 5.7 which shows a set of five distributions obtained for a mixture of A/75% CH_4 using a fixed drift length (4.0 cm) and a constant E/p (0.4 V cm⁻¹ torr⁻¹) at different pressures. The distributions show a clear variation in the position of the peak. That is the transit time of electrons from the photocathode to the anode. This variation can be explained by considering the flight path of electrons to consist of three parts, the cathode-grid space, the drift space and the proportional counter (from the aperture to the anode). In the first part the height of the cathode control pulse (~40 V), was constant yielding a field $E \sim 200$ V cm⁻¹. Therefore, E/p in that region depended only on the pressure. Accordingly the drift velocity and hence the transit time of the electrons in the cathode-grid space was a function of pressure. In the drift region the field was uniform and could be set to yield the value of E/p required. In this experiment the E/p value was constant for all pressures. Accordingly the transit time in the drift space was constant too. In the proportional counter application of the anode voltage was determined by the operating conditions. The anode voltage was set to maintain approximately constant operating conditions at all pressures. Hence the E/p values changed according to the values of the field and the pressure. Accordingly the transit time in the proportional counter part of the path was variable. Clearly the variation in the position of the peak was caused by changes in the transit times of electrons in the cathode-grid space and the proportional counter due to E/p variations in these regions. Since in the present drift velocity

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measurements a differencing procedure was applied, these end effects were eliminated. Drift velocity measurements carried out using this procedure showed no pressure dependence. For a gas mixture of A/10% CH₄ a series of runs was carried out at different pressure values, 1 atmosphere, 400 torr and 200 torr. Measurements covered ranges of E/p, $(0.1 \text{ to } 0.5) \text{ V cm}^{-1} \text{ torr}^{-1}$ at atmospheric pressure (measurements at this pressure were limited by the drift voltage), and (0.1 to 0.8) Vcm⁻¹ torr⁻¹ at 400 torr and 200 torr. The drift velocity values obtained at the same E/p, at different pressures were found to agree to better than ±3% (the limits of the experimental error). Advantage was, therefore, taken from this property of drift velocity pressure independence to extend the range of measurements to cover a larger E/p range.

For D/μ measurements, again, no pressure dependence was observed.

6.3 Effects of impurities

Various aspects were investigated in this area. Experimentally, the effects of such factors as outgassing, the use of a drying trap in the flow line, gas flow rate and leakage, on drift velocity measurements were examined. Calculations were also carried out to examine the effect of water vapour on drift velocity values. The accuracy of the proportions of one mixture (Ar/10% CH_4) was assessed.

6.3.1 Effect of outgassing on drift velocity measurements

The effect of outgassing from a number of materials on drift velocity results was investigated.

In the early stages of drift velocity measurements the cathode pulser was enclosed within the experimental chamber. The presence of the pulser within the chamber had introduced considerable outgassing. This was discovered when drift measurements carried out at atmospheric pressure showed marked dependence upon gas flow rate. For a gas mixture of Ar/10% CH₄, measurements were carried out at a single E/p value, 0.2 V cm⁻¹ torr^{-1*} and using different flow rates, (20, 80 and 150 cc/min). The results obtained in that experiment are as follows:

flow rate	W cm/µs		
cc/min			
20	4.36		
80	4.81		
150	5.12		

(The final drift velocity value at E/p = 0.2 for Ar/10% CH₄, measured under optimised conditions, i.e. independent of flow rate, was 5.62 cm μ s⁻¹.) The results of this experiment indicated clearly a presence of high levels of impurities. In tracing the possible sources of contamination, the first step taken was to move the pulser to the outside. This eliminated the apparent dependence of W on flow rate. The presence of the pulser within the chamber and with its electronic components being at higher temperatures relative to the surroundings had, apparently, increased the outgassing rate which seriously degraded the drift velocity results.

Organic materials are known to outgas excessively. In the system used in this work, use of these materials was kept to a minimum. The largest organic component used was PVC. The major PVC part of the

This E/p value was chosen because calculations carried out in this work indicated that the corresponding W-value for the mixture is about maximum. This maximum occurs when the mean electron energy is in the vicinity of the Ramsauer minimum. Under these conditions W values are very sensitive to impurities.

system was the tubing employed in connecting together various sections of the gas handling facility. The overall length of PVC tubing used was about 1.5 m. To examine the effect of PVC on drift velocity, an experiment was carried out in which a 30 m long piece of PVC tubing was used to connect a gas cylinder (Ar/10% CH_{*}) to the inlet of the chamber <u>via</u> a drying trap. In that experiment no obvious dependence of W on flow rate was observed. However, at E/p = 0.2 (the setting at which the examination was carried out) the drift velocity value was about 5% below the final result obtained under optimised conditions. In another experiment the normal PVC connecting tubes were replaced by silicon-rubber tubes. In that experiment no significant change was observed in the value of W, at E/p of 0.2. Both results were in agreement within the limits of experimental error (±3%).

6.3.2 Leak rate

The effective leak rate of the system was determined from the ratio of static leak rate measured to the gas flow rate.

Using a rotary pump the system was evacuated to the highest possible vacuum attainable with this type of pump. After twelve hours, during which the system had been sealed off, a pressure change of 3 torr was observed. With an estimated chamber capacity of 2 litres, the leak rate (including outgassing from internal components) was 0.5 litre torr h⁻¹. At atmospheric pressure this amounts to, 1.8×10^{-4} cc s⁻¹. The normal gas flow rate used in measurements carried out at atmospheric pressure was 40cc/min. Therefore, the maximum effective leakage impurity level was 2.7×10^{-2} %.

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6.3.3 Effect of water vapour on drift velocity

It is now a well established fact that transport coefficient for argon are very sensitive to impurities (Bowe 1960; Uman 1964; Compton et al. 1972). The effect is particularly pronounced when these impurities have large, low-energy, cross-sections as, for example, water vapour. Since argon was a main component of most gas mixtures studied in the present work, it was of interest to examine the effect of a small fraction of water vapour on drift velocity values for one of these mixtures. Some calculations^{*} were carried out for a mixture Ar/10% CH4, using the programme presented in appendix I. Figure 6.1 shows the effect of 0.2% water vapour. (In the calculations the water vapour cross-section used was that derived by Pack, Voshall and Phelps 1962.) Although the suppliers quote 2 Vpm, a typical content of moisture in Ar/10% CH4 a close resemblance was observed between measured drift velocity values (E1-Hakeem and Mathieson 1978) and those shown in figure 6.1 for 0.2% water vapour. This suggested that the discrepancy^{\dagger} between the measured and calculated result might have been due to a presence of excessive amounts of moisture in the mixture. Nevertheless, using the drying trap described in section 4.2.5 did not alter measurements significantly.

^{*} Different cross-sections from various sources for argon and methane were used in the calculation of transport parameters carried out in this work. These will be discussed in the next chapter. In the calculation discussed above the cross-sections used were the elastic and inelastic cross-sections for methane derived by Duncan and Walker (1973) and the imperical expressions of Palladino and Sadolet (1975) for Ar elastic cross-section.

[†] Better agreement was found by employing a different Ar cross-section (section 7.2.1).



6.3.4 Gas composition

To assess the accuracy of proportions of gas mixtures (supplied ready mixed by BOC), studied in the present work and to examine the reproducibility of results, a series of runs was carried out using three different Ar/10% CH, cylinders. Measurements covered a range of E/p, 0.1 to 0.7, in steps of 0.1. The runs were carried out under the same experimental conditions. The system was evacuated in between the runs. The results obtained with the first and the third cylinders were in good agreement within the limits of experimental error (±3%). Results obtained with the second cylinder, however, were systematically about 7% below those of the other cylinders. At E/p = 0.2, and at atmospheric pressure measurements were repeated for all three cylinders. The results that had been obtained earlier were reproduced within the limits of error.

Calculations carried out during the course of this work indicated that the sensitivity of drift velocity, in the saturation region, to changes in the fraction of methane in argon is

$$\frac{\Delta W}{W} \simeq 0.05/\%$$
 methane

An estimate based on these calculations and the results obtained using the first and the third cylinders, indicates that W-values observed using the second cylinder would have been yielded, with the present system, had a gas mixture of Ar/8.7% CH4 been used. For A/10% CH4, the suppliers quote a mixing accuracy of $\pm 0.65\%$. However, from the discussion above it seems likely that errors in excess of the suppliers specifications may be found.

6.4 Effects of geometrical parameters on drift velocity measurements

6.4.1 Drift length

With the time-of-flight apparatus that was finally adopted for drift velocity measurements, observed time intervals corresponding to various drift length intervals were consistent to better than 2%. This was a clear indication that drift velocity was independent of drift length.

6.4.2 Aperture size

A range of circular apertures of diameters ranging from 1.0 mm to 10.0 mm were used to examine the effect of aperture size on drift velocity. The results obtained with these apertures may be summarised by considering the two extremes.

Measurements using an open circular, 1.0 mm diameter aperture were extremely consistent. However, the count rate was very low (a few counts per second). Results observed with an open 10 mm diameter aperture, on the other hand, indicated a clear dependence of drift velocity on drift distance. Figure 6.2 shows two, distance/time, sets of results observed at atmospheric pressure, at $E = 150 \text{ V cm}^{-1}$, and 300 V cm^{-1} for Ar/10% CH₄. Drift velocity values, determined from the linear part of the curves, were about 50% below those measured using the 1.0 mm diameter aperture. Two possible factors were considered for explaining the drift velocity/drift distance dependence observed in this experiment. The first factor is drift field distortion resulting from penetration of the anode field into the drift region. Secondly, positive ions may leak through the aperture causing a reduction of the magnitude of the drift field and hence the drift velocity. However,

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An arrival time distribution obtained with a large aperture (1 cm. diameter). Fig. 6.3

calculations indicated that the effect of the second factor is negligibly small compared with that of the first (section 6.5.6). By covering the 10 mm diameter aperture with a stainless steel gauze of the type described in section 5.3.2, the length/time relationship was more linear. Nevertheless, arrival time distributions indicated that a substantial number of electrons from the end of swarms had been recorded. This can be seen in figure 6.3 which shows a typical distribution observed using the aperture described above. This is clearly in violation of the C/F criterion.

To increase the count rate and hence speed data accumulation, a rectangular slit covered with a copper micromesh was employed. Drift velocity measurements obtained with this showed no distance dependence and were in agreement with those observed using the 1.0 mm diameter aperture.

6.5 Electronic effects on drift velocity

6.5.1 Electronic noise

Electronic noise in a time-of-flight system results in a spread in the experimentally measured cross-over time and this in turn leads to broadening arrival time distributions. It is important, therefore, to assess this effect. It is necessary, first, to measure the noise of the preamplifier. This measurement was carried out using the test system of figure 4.13. The PHA which had been calibrated in voltage, was supplied with a pulse from the precision pulse generator via the preamplifier (test input) and the linear amplifier. Knowing that the calibration capacitor ($C_T = 1.0 \text{ pF}$) and from the FWHM of the distribution observed, the rms noise charge, was determined. For the preamplifier

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used a typical value of rms noise charge was 274 e.

Now let us consider the effect of the preamplifier noise on the TAC output. As an approximation, assume that the proportional counter delivers a current impulse of strength q_o . Then the preamplifier output (figure 6.4) is a step of height q_o/C_o , and the shaping amplifier output is given by:

$$v_o = \frac{q_o}{C_o} A_o L^{-1} H(S)/S$$

where AH(jw) is the amplifier transfer function and L^{-1} represents the inverse Laplace transform. In principle, if H(jw) is known, then we can calculate v_0 and hence the slope of the waveform at cross-over.



Figure 6.4: Effect of preamplifier noise on TAC output.

Let us denote this slope as $(q_o/C_o)A_og_x$. If the preamplifier equivalent noise charge is q_n then the rms noise from the shaping amplifier is, by definition, Δv_o given by

$$\Delta v_o = \frac{q_n}{C_o} A_o a$$
 where $a \equiv [L^{-1} H(S)/S]_{max}$

The rms spread in cross-over time is therefore given by



$$\Delta \mathbf{t}_{\mathbf{x}} = \frac{\mathbf{q}_{\mathbf{n}}}{\mathbf{q}_{\mathbf{o}}} \frac{\mathbf{a}}{\mathbf{g}_{\mathbf{x}}}$$

The exact calculation of a and g_x for the Ortec amplifier would be rather lengthy and not justified. However, a reasonably good approximation to the Ortec filter, in the bipolar mode, is

H(S) =
$$\frac{S^2/T}{(S+1/T)^3}$$
 where T is the time constant

With this filter it can be shown that a = 0.2306 and $g_x = 0.1353/T$. Thus:

$$\Delta \mathbf{t}_{\mathbf{x}} \simeq \left(\frac{\mathbf{q}_{\mathbf{n}}}{\mathbf{q}_{\mathbf{o}}}\right)^{\mathrm{T}} \cdot 1.7 \tag{6.1}$$

(Probably a numerical factor ~ 2 rather than 1.7 would be more correct; however, the calculation will only be used to estimate $\Delta t_{\mathbf{x}}$.)

An experiment was carried out (using the test system) in which Δt_x (rms) was measured over a range of input charge pulse from 5.10^{-15} to $4.2.10^{-14}$ C and with T = 0.25 µs. Figure 6.5 shows the results obtained for Δt_x as a function $1/q_o$. It can be seen from the diagram that under the conditions above the largest value of Δt_x , which occurs at threshold, is ~34 ns (rms). Now equation 6.1 may be verified. For T = 250 ns, $q_n = 274$ e (rms) and using the rms value of q_o at threshold (~4560 e), $\Delta t_x \simeq 30$ ns.

6.5.2 System linearity

One of the prime factors governing the accuracy of drift velocity measurements is linearity of the electronics. In the present system high degree of linearity was achieved by optimising the bias to the tunnel diode of the cross-over detector such that the peak corresponding



Fig. 6.6 A set of distributions obtained using charge pulses ranging from 5.10^{-15} C to $4.2.10^{-14}$ C.

to a certain delay between start and stop pulses (figure 4.14), was insensitive to stop input amplitude variations. (The theory of optimum tunnel diode biasing is well known and need not be repeated here, see for example Herbst 1970.) For an optimised cross-over detector a standard deviation of better than 0.5% was measured over a range of input pulse amplitudes from 5.0 mV (threshold) to 42 mV (just below saturation limit of the linear amplifier). [See figure 6.6.]

Linearity of the electronic logic was tested with the time calibration procedure. Calibration procedure carried out using an input test pulse amplitude about 20 times rms noise, indicated that the system was linear to better than 0.1%.

6.5.3 Effects of cathode pulse width and cathode/grid bias

As discussed in chapter 4, it was possible to control the counting efficiency, C/F by three means, repetition rate F, cathode pulse width τ , and cathode-grid bias V_{CG} . An experiment was carried out to examine the effect of the two latter factors on count rate, C, and the effect of τ change on arrival time distribution spread. Table 6.1 shows three sets of results obtained using cathode-grid biases of 0.0 V, 2.7 V and 5.4 V, and at various values of τ . The results were observed under the following conditions:

gas	-	Ar/10% CH4
pressure	-	atmospheric
E/p	-	$0.2 \ V \ cm^{-1} \ torr^{-1}$
repetition rate	-	100 s ⁻¹
drift distance	-	2.0 cm

TABLE 6.1

τ(ns)	V _{CG} 0.0V		V _{CG} 2.7V		V _{CG} 5.4V	
	count rate* (s ⁻¹)	FWHM† (ns)	count rate FWF (s ⁻¹) (ns		count rate (s ⁻¹)	FWHM (ns)
20						
42	3	151				
62	7	158	2	151		
83	9	158	5	158		
104	13	165	10	180	5	165
122	18	180	14	180	9	180

Observed variations of count rate and FWHM with τ and $V_{\mbox{CG}}.$

For all τ settings no genuine counts were observed at $V_{\textbf{CG}} > 5.4~V.$

6.5.4 Coincidence mode

After the introduction, in the time-of-flight system of the cathode pulser and the modifications associated with it, arrival time distributions showed a presence of a secondary peak occurring at an earlier time than a main peak (figure 6.7). With the secondary peak always being less intense than the main peak, it was initially thought that it had resulted from photo-emission from the grid. On these lines two tests were carried out in order to confirm or eliminate this possibility. In the first test the grid was replaced by an open circular hole of

* The background count rate is subtracted.

† These are only approximate values as observed visually on the PHA.



Fig. 6.7 A double peaked distribution observed in an anti-coincidence mode of operation of PHA.

diameter 6 mm. The second test involved using a photocathode with a thicker gold film. The results of both tests failed to confirm the initial explanation. A third test was made in which the mode of operation of the PHA was changed from an anti-coincidence to coincidence. This resulted in the elimination of the secondary peak. Operating the system in the coincidence mode revealed that the secondary peak had resulted from large amplitude pulses overloading the linear amplifier. These were discriminated against using a SCA (figure 4.6).

6.5.5 Effect of positive ions

In a proportional counter generation of positive ions takes place mainly in the immediate vicinity of the anode. Positive ions then drift in all directions away from the anode until they reach the walls of the counter where they will be collected. In a system of a configuration such as that used in the present work, a fraction of positive ions generated in the counter may drift through the aperture into the drift region. We may now use a very simple argument to assess this effect on electron drift velocity applying some extreme conditions.

Consider a cylindrical volume of cross-section A and length h. Let A be the area of an aperture between the counter and the drift region, and h be the drift length. Assume that a fraction, f can pass through the aperture and can only travel within the volume Ah. Now, if the charge from the counter per pulse is q_0 and the count rate is n, then the positive ion through the aperture is f q_0 n and the current density is $\frac{f n q_0}{A} = \rho v_+$ where ρ is charge density and v_+ is positive ion velocity. From Gauss's theorem we have:

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$$\frac{dE}{dx} = \frac{\rho}{\epsilon_0}$$

where x is the direction of the electric field E, and ε_0 is the permittivity of free space. If E₁ and E₂ are the fields at x = 0 and x = h, then

$$E_1 - E_2 = \Delta E = \frac{h\rho}{\varepsilon_0} = \frac{f q_0 n h}{A v_1 \varepsilon_0}$$

Example: for $q_0 \sim 10^{-14}$ C, $n \sim 100$ s⁻¹, $v_+ \sim 1$ m s⁻¹, f=1.0, h= 5×10^{-2} m, A=10⁻⁴ m² and $\varepsilon_0 = 8.85 \times 10^{-12}$ F m⁻¹ the change in field ΔE is of the order 0.1 V m⁻¹.

Positive ions may, therefore, alter an experimentally set field value giving a false drift velocity value. Clearly this effect is negligibly small in the present case.

6.5.6 W-measurements using a continuous wave UV source

Employing an electronically pulsed photocathode in the time-offlight apparatus used in this work made it possible to measure drift velocities using a CW UV source. Some measurements were carried out at frequencies ranging from 5 KHz to 50 KHz and at a constant pulse width of 100 ns yielding $C/F \sim 10^{-3}$. Comparison between results obtained with pulsed and CW sources indicated the following:

Distributions obtained using the CW-mode were noisier than those obtained with the pulsed UV source. One possible explanation considered laid stress on the fact that the CW source used was relatively more powerful. This might have resulted in UV photons penetrating into the drift region and interacting with gas molecules. 'CW'-distributions were less symmetric than those obtained in the pulsed UV mode. Computer

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analysis of the 'CW' data indicated a random error in drift velocity values $\pm 6\%$ as compared with 2% in the pulsed mode. Within these limits, however, results observed in both mode were in agreement. When used continuously for an extended period (> 1h), the CW source showed a sign of instability resulting in deterioration of count rate. For these reasons employing a pulsed UV source was more favourable for drift velocity measurements.

6.6 Various effects on lateral diffusion measurements

A series of experiments was carried out in order to investigate the reliability of the method used, in the present work, to measure lateral diffusion. A number of parameters (mainly geometrical), were varied in these experiments.

6.6.1 Drift length and axial alignment

Variation of drift length within the system used in the present studies was a useful provision for examining the accuracy of axial alignment of the receiving electrode. As discussed in section 5.4, for an accurately aligned system a graph of $\frac{1}{\log(1+2r)}$ versus h, yields a straight line passing through the origin. To verify this, the geometrical axis of the system was displaced laterally, along one of the alignment axes, by about 1.0 mm with respect to the centre of the receiving electrode and measurements were carried out in the normal manner (section 5.4). Figure 6.8 shows two sets of results obtained with the system axially aligned and seriously misaligned. In this experiment Ar/10% CH₄ was used and measurements were made at atmospheric pressure at E/p= 0.2 V cm⁻¹ torr⁻¹.



6.6.2 Effect of source-hole size on D/μ

The magnitude of error, in λ (=W/2D), resulting from the use of a source hole of finite size was calculated by Crompton and Jory (1963). By considering the source hole as made up of a series of annular sources of increasing diameter and assuming a uniform electron distribution over the entire area of the hole, these authors applied their calculations to a hole of 1 mm diameter and different combinations of the parameters b and h. Their results suggest that the error in the current ratio, R depends mainly on the size of the central collector and less dependent on the drift length. The maximum error, as indicated by Crompton and Jory results, is of the order 0.7% at R=0.8 and for b=0.5 cm.

In this work a similar investigation was carried out experimentally to assess approximately the magnitude of error in D/μ due to the size of the source. With the present apparatus having a central collector of a fixed radius (0.125 cm), it was more convenient to vary the size of the source hole. Three source holes of diameters 0.9, 1.25 and 1.5 mm were used. Figure 6.9 shows the variation of D/μ with source diameter as measured in A/10% CH₄ at a set of E/p values. It appears, as the results show, that D/μ values will not change significantly if the diameter of the source hole is reduced below 0.9 mm. On the basis of these results it is estimated that the error introduced in D/μ by using a source of 0.9 mm diameter is about 1%.

6.6.3 Effect of current ratio R on D/μ

Calculations carried out in this work indicated that, for the gases studied, D/μ covers a wide range of values at E/p values of

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interest. With the present apparatus limited by the dimensions described in section 4.2.4, this involved using a wide range of current ratios, R. To assess the effect of R on D/μ results a series of measurements, covering current ratios from about 0.175 to about 0.7, was carried out. Figure 6.10 shows, for A/10% CH, variation of D/μ with R at various E/p values. The results show clearly strong dependence of D/μ on R near the limits of the range of R covered. This effect was rather puzzling and no simple explanation for it could be found. From the results presented in figure 6.10 and similar results obtained for other gas mixtures, an experimental correction factor for D/μ due to the effect of R was worked out (figure 6.11). Estimation of this correction was based on the assumption that optimum current ratio for determining D/μ is 0.5 (Huxley and Crompton 1974). The diagram of figure 6.11 was used to correct measured D/μ values presented in this thesis.

CHAPTER 7
NUMERICAL AND EXPERIMENTAL RESULTS

7.1 Numerical Results

Using the assumptions discussed in section 2.7, the modified Boltzmann-Holstein equation was employed to calculate W and D/μ , and other related parameters for various gas mixtures involving the components argon, methane, neon, carbon dioxide and water vapour. The temperature for all calculations was 290°K.

7.1.1 Cross-sections

Numerical values for the interaction cross-sections for the gas components studied were obtained from various sources, referenced below, either as empirical equations or in tabulated form. In the latter case if a piece-wire linear or exponential very close fit could not be found, then a cubic-spline interpolation routine was used. We now proceed to consider the cross-sections used.

(i) Argon:

The argon momentum transfer cross-section has been derived in detail fairly recently by Milloy <u>et al</u>. (1977) to analyze the recent drift velocity measurements of Robertson (1977) and the lateral diffusion measurements of Milloy and Crompton (1977). For the present calculations the numerical cross-section was obtained by cubic spline interpolation of the tabulated data given by Milloy <u>et al</u>. This cross-section gives, as of course it must, calculated drift velocities and lateral diffusion coefficients in excellent agreement, respectively with the Robertson, and the Milloy and Crompton data. It should be especially noted that Robertson's measurements differ very considerably from those of Pack and Phelps (1961) for E/N values less than about 10^{-2} Td. This is particularly important in the present context since these two sets of measurements are the only ones which extend to low E/N values to be useful for determining the argon cross-sections below about 0.5 eV, that is to embrace the main portion of the Ramsauer dip (Milloy <u>et al</u>. 1977). The empirical equations for the argon cross-section given by Palladino and Sadoulet (1975), and also employed by Schultz and Gresser (1978), describe the cross-section derived by Frost and Phelps (1964) using the Pack and Phelps drift velocity data. The computer programme, employed in the present calculations, if used with the Palladino and Sadoulet cross-section produces accurately the Pack and Phelps velocities. However the Robertson velocity data, the Milloy and Crompton lateral diffusion data and the Milloy <u>et al</u>. cross-section, are now considered to be more accurate representations of the situation.

(ii) Methane:

The methane inelastic cross-sections were obtained by cubic-spline interpolation from data supplied by Walker (private communication). These data have been plotted in the paper of Duncan and Walker (1972) in which they describe the experimental measurements and the theoretical reasoning leading to these cross-sections. They argue that to match calculated and experimental transport coefficients it is necessary to consider two vibrational excitation processes, one with excitation threshold at 0.162 eV and the other at 0.374 eV. Both derived inelastic cross-sections have the same shape, reaching a maximum of about 6.10^{-17} cm² shortly above threshold, falling rapidly to about 2.10^{-17} cm². It should be noted that this description is quite different from the inelastic cross-section chosen by Palladino and Sadoulet (1975) and Schultz and

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Gresser (1978) which is finite only <u>below</u> an energy threshold, at 0.36 eV. Apart from being rather unrealistic physically such a cross-section cannot be considered within the present formulation since the inelastic scattering term would vanish.

Two versions of the methane elastic cross-section have been considered during the present calculations. One was obtained by cubicspline interpolation on the tabulated data of Duncan and Walker (1972) while the other was calculated using the simple empirical formula given by Palladino and Sadoulet (1975). [The effect of both versions of methane elastic cross-section on the numerical results will be discussed further; section 7.2.1.]

(iii) Neon:

The neon momentum transfer cross-section for electron energies up to 7 eV was obtained by cubic-spline interpolation of the tabulated data of Robertson (1972). Values of drift velocity calculated with the present programme, for 100% neon, agree extremely closely, as of course they must, with Robertson's experimental values (provided the average electron energy remains small compared with 7 eV; this upper energy limit ε_{L} of course can not exceed the range of available cross-section data).

(iv) Carbon dioxide:

Hake and Phelps (1967) have derived momentum transfer and inelastic cross-sections for carbon dioxide. For the present calculations, numerical data for the inelastic cross-section were obtained using a piece-wire linear and exponential fit to the four vibrational excitation curves given by Hake and Phelps. The four threshold energies are 0.08, 0.3, 0.6 and 0.9 eV with very sharply peaked excitation cross-sections

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with maxima of about 3.10^{-16} , 5.10^{-16} , $3.2.10^{-16}$ and $2.2.10^{-16}$ cm² respectively. The momentum transfer cross-section was obtained, initially, by cubic-spline interpolation of Hake and Phelps' tabulated data. These cross-sections yielded, as expected, drift velocities in good agreement with experimental measurements (Elford 1966).

Schultz and Gresser have observed, however, that the elastic crosssection obtained by Brode (1933) (for which they give an empirical equation) also reproduced well the experimental drift velocity results and, further, this gave better agreement for argon/carbon dioxide mixtures than the Hake and Phelps elastic cross-section. This is confirmed in this work; for the calculations presented in this thesis the Schultz and Gresser (Brode) elastic cross-section was used. It is emphasised, however, that the inelastic cross-section was that derived by Hake and Phelps as described above. As discussed previously for methane, the type of inelastic cross-section employed by Schultz and Gresser is not suitable for the present formulation. It may also be remarked here that, under typical W and D/μ conditions, the average electron energy is of the same order as the inelastic threshold. It is therefore of questionable validity to use a Taylor expansion involving the energy distribution with the threshold energy as the interval.

7.1.2 Asymmetry ratio <f1/f0>:

Figures 7.1 (a) and (b) show the asymmetry ratio (section 2.6) plotted against E/p for the various gases studied in the present work. From these diagrams it can be clearly seen that the asymmetry ratio is not always small compared with unity. This shows that expressing the distribution function only by the first two terms of the series given by equation 2.2, is not in general, justified. [The effect of the









asymmetry ratio on the accuracy of the calculations will be considered further in the discussion of the experimental results.]

<u>7.1.3 Mean electron energy $\bar{\epsilon}$:</u>

Figures 7.2 (a) and (b) show the variation with E/p, of the mean electron energy for the various gases studied. One of the factors governing the reliability of the present calculations is that the mean electron energy remains small compared with the upper energy limit, ε_{L} , employed. In these calculations choice of ε_{L} was determined by the availability of section data.

7.2 Experimental drift velocity results and discussion

7.2.1 Argon/methane mixtures:

For comparing the experimental results obtained in this work and those determined by other workers with theoretical predictions, crosssections obtained from various sources were employed in the calculations. Here the methane cross-sections used were obtained, as discussed in section 7.1.1, from the data of Duncan and Walker (1972) inelastic cross-sections and from the empirical equation of Palladino and Sadoulet (1975) for momentum transfer cross-section. With these, calculations were carried out using, separately, the Milloy <u>et al</u>. (1977) and the Palladino and Sadoulet (Frost and Phelps) argon empirical equations.

Figure 7.3 shows, for Ar/10% CH₄, drift velocities measured by Bortner <u>et al</u>. (1957), English and Hanna (1953) and those measured in the present work, compared with calculations. The English and Hanna and the present measurements are seen to be closer to the calculations using the Milloy <u>et al</u>. argon cross-section (curve a) than that using

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the Palladino and Sadoulet equations (curve b). These two sets of measurements are in fair agreement at E/p above about 0.3 V cm⁻¹ torr⁻¹. Comparing the present measurements with the calculations (curve a) one can see that there are two main regions of marked discrepancy, near the peak and the region at E/p above 0.8 V cm⁻¹ torr⁻¹. The peak velocity value, as can be seen from figure 7.3, is at $E/p \sim 0.2 V \text{ cm}^{-1} \text{ torr}^{-1}$. At this E/p value the mean electron energy, as figure 7.2(a) shows, is of the order 0.23 eV. The argon cross-section at this energy shows an extremely pronounced Ramsauer effect, with a very small minimum value less than 10^{-17} cm². The methane inelastic cross-section is therefore actually considerably greater than the argon elastic cross-section over part of the energy distribution. A second feature is that, because of the low mean electron energy and high drift velocity, the asymmetry ratio in the region of maximum drift velocity, (figure 7.1a), is necessarily large. These two factors, the small ratio of elastic to inelastic scattering and the large asymmetry ratio, suggest that at present, limited reliance only should be placed on theoretical predictions such as these even if accurate cross-sections are employed.

The second main region where large discrepancy occurs between the observed and predicted results is at E/p values above 0.8 V cm⁻¹ torr⁻¹. In this region the theoretical curve appears to decrease more rapidly than experimental measurements. This apparent discrepancy can not be followed to much larger values of E/p since, as figure 7.2a shows, the mean electron energy increases rapidly with increasing E/p. The electron energy distribution would then extend significantly into regions for which cross-sections are unavailable or in which the present theory is inapplicable.

In addition to the theoretical limitations discussed above, one

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can not dismiss effects of experimental factors. In the present system, as discussed in preceding chapters, measurements of distance, time and voltage, and the reproducibility of the experimental results are sufficiently accurate. Gas contamination therefore, is one possible factor that might have contributed to the discrepancy. Although the measured outgassing and leak rate was negligible compared with gas flow rate, it is possible that some form of trapping mechanism was occurring with one of the impurity components. In this case the crosssection for such a process would have to be very large to alter the measurements significantly.

Figure 7.4 shows, for Ar/50% CH4, the present experimental drift velocity results and those of English and Hanna compared with the theoretical calculations. Over most of the E/p range used by English and Hanna, the disagreement between the two sets of measurements is disturbingly large. It seems that the experimental limitations of the English and Hanna method discussed in section 3.4 are largely responsible for the discrepancy. Comparison between the present measurements and the calculations shows rather better agreement than for A/10% CH4.

Figure 7.5 shows a comparison between the measured drift velocity values and the theoretical calculations for the mixture A/75% CH₄. As can be seen here the agreement is better than both for 10% and 50% mixtures.

<u>7.2.2 Methane:</u>

Figure 7.6 shows the calculated drift velocities for 100% methane using the cross-sections discussed in section 7.1.1(ii). Some experimental points of English and Hanna, and Wagner, Davis and Hurst (1967) are shown together with the present measurements. The latter two sets

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٠. , 4...P . of results are in good agreement. The agreement between experiment and calculation is moderately good. The calculation using the Duncan and Walker cross-section (curve a) appears to be in closer agreement with experiment than that using Palladino and Sadoulet cross-section (curve b), at low E/p values whereas the reverse is true at high E/p values.

As can be seen from figure 7.1.1 that for 100% methane, as in the case of A/CH_4 mixture, the asymmetry ratio is very high. The effect of this on the calculations, however, is not as serious as discussed in the preceding section since the elastic cross-section for methane does not fall as low as for argon.

7.2.3 Neon/methane:

For the mixture 90% neon, 10% methane no drift velocity data could be found in the literature for comparison with the present measurements. Figure 7.7 shows the calculated results for the mixture together with the experimental values obtained in this work. The agreement is seen to be satisfactory. [These calculations employed the Duncan and Walker methane elastic cross-section.] One is confident that use of the cross-section data of Robertson (1972) for neon, and of Duncan and Walker, or of Palladino and Sadoulet for methane in the modified Eoltzmann-Holstein formulation (section 2.6) allows meaningful prediction of electron transport coefficients and energy distributions in reon/methane mixtures (for E/p values such that $\bar{\varepsilon}$ remains small compared with ε_L). The predictions presumably become somewhat less reliable as the methane component predominates because of the uncertainty in the nethane elastic cross-section. One is also confident that the experinental results for the neon/10% methane mixture are more reliable than those of the argon/methane mixtures. The reproducibility of the

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measurements here was better than that of the argon mixtures (<2%). Further for the Ne/10% CH4 mixture the average random error in the individual velocity points, as determined by a least square data fitting procedure, was better than 1%.

The main discrepancy between the experimental and calculated results, as figure 7.7 shows, is at E/p values in excess of 0.8 V cm^{-1} torr⁻¹. In this region the theoretical calculations appear to fall systematically below the experimental values. Further cross-section data are really required. As E/p increases the average electron energy increases rapidly, as shown in figure 7.2(a). Thus for the neon/10% methane mixture at E/p much in excess of 1 V cm⁻¹ torr⁻¹, the high energy tail of the energy distribution extends significantly into regions for which the methane cross-sections are unknown (\geq 5 eV) or the neon cross-section is unknown (>7 eV).

7.2.4 Argon/carbon dioxide mixtures:

This situation is rather similar to that for argon/methane mixture. However, there are some aspects which require special comment.

Comparison between measured and calculated drift velocities are shown in figures 7.8, 7.9 and 7.10 for the mixtures A/10% CO_2 , A/5% CO_2 and A/3% CO_2 respectively. The cross-sections used in these calculations, as discussed in section 7.1.1, were the Milloy <u>et al</u>. (1977) argon cross-section, the Hake and Phelps (1967) carbon dioxide inelastic cross-section and the Schultz and Gresser (Brode) carbon dioxide elastic cross-section. The agreement between experiment and prediction for the three mixtures is poor, possibly for the same reasons discussed for argon/methane mixtures. The inelastic cross-section maxima in carbon dioxide greatly exceed the Ramsauer minimum in the argon cross-section.

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Further, as shown in figure 7.1(b), the asymmetry ratio reaches quite large values. The experimental results for the three mixtures, on the other hand, seem to share some common features. Maximum velocity value appears to occur at a lower E/p value than that of the theoretical maximum. A second common feature is that the experimental values appear to be higher than the theoretical at low E/p values whereas the reverse is true at high E/p values. Examination of the theoretical curves for the three A/CO_2 mixtures indicates that the value of E/p at which a drift velocity maximum occurs depends on the carbon dioxide concentration. The apparent shift of the position of drift velocity peak along the E/p axis is approximately 0.1 V cm⁻¹ torr⁻¹/% CO₂. Therefore one can not rule out the possibility of error in the proportions in excess of that quoted by the supplier. A more basic cause for the disagreement between the theoretical predictions and the experimental measurements is the possibility of significant error in the carbon dioxide cross-section. The momentum transfer and inelastic crosssections for carbon dioxide are still by no means as firmly established as the argon cross-section.

7.3 Experimental D/μ results and discussion

Due to serious time limitation, measurement of ratio of lateral diffusion to electron mobility, D/μ was restricted to four mixtures A/10% CH₄, A/50% CH₄, Ne/10% CH₄ and A/3% CO₂, thus involving all gas components considered in this work. The experimental results which will be discussed in the subsequent sections are compared with calculations involving the same cross-sections, discussed in preceding sections, used in drift velocity calculations. Measured D/μ values are corrected for current ratio, R, effect, discussed in section 6.6.3,

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using the experimental correction factor of figure 6.11. For the mixtures studied no data could be found in the literature for comparison.

7.3.1 Argon/methane mixtures

(i) A/10% CH₄:

Figure 7.11 shows, for A/10% CH₄, measured D/μ values plotted against E/p, together with calculated results. The agreement between theory and experiment at E/p above 0.4 V cm⁻¹ torr⁻¹ is good and over the whole range of E/p, is satisfactory. The region of disagreement here is that which corresponds to, as figure 7.1 shows, the region where the Ramsauer minimum occurs. The discrepancy between prediction and measurement in D/μ results in this region, however, is not as large as in drift velocity results (figure 7.3). The discrepancy here may be explained in terms of experimental or theoretical factors, or, indeed a combination of the two aspects. With the present system and at E/p below 0.2 V cm⁻¹ torr⁻¹, current ratios involved in measurements were relatively high and lie in the region where D/μ depends strongly on R (figure 6.11). Although results are corrected empirically for this effect there is an uncertainty in the magnitude of error due to R near the extremes of the correction curve of figure 6.11. From a theoretical viewpoint the discrepancy may be explained by similar argument to that of drift velocity discussion of section 7.2.1. That is, the reliability of calculations in this region is limited by the large asymmetry ratio and the small ratio of elastic cross-section (argon) to inelastic crosssection (methane). D/μ results at $E/p \ge 0.4$ V cm⁻¹ torr⁻¹, on the other hand, are more reliable. The effect of the theoretical limitations

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discussed above is small, and the experimental measurements involved current ratios which lie in the region (figure 6.11) where the dependence of D/μ on R is minimal.

(ii) <u>A/50% CH4</u>:

Comparison between measured and calculated results for this mixture is shown in figure 7.12. There is agreement between prediction and measurement at E/p values below $0.5 \text{ V cm}^{-1} \text{ torr}^{-1}$. At E/p above 0.5, however, the disagreement is too large to be attributed to experimental factors alone. Here, again, the region of maximum discrepancy corresponds to that where electron energy is in the vicinity of Ramsauer minimum (figure 7.1). It is interesting to note that agreement between drift velocity measurement and calculation for A/50% CH₄ (figure 7.4) is better than for A/10% CH₄ (figure 7.3), whereas the reverse is true here.

7.3.2 Neon/10% methane:

A comparison between calculated and measured results for this mixture is shown in figure 7.13. The agreement here is good over the range of E/p covered. D/μ measurements for Ne/10% CH, involved employing current ratios in the range 0.3 to 0.55 (figure 6.11). In this range dependence of D/μ on R is minimal. This makes the experimental results for the mixture more reliable than, for example, those for A/50% CH, where measurements involved using large values of R. Further Ne/10% CH, results were reproducible to better than 2%. The asymmetry ratio for the mixture, as figure 7.1(a) shows, is relatively low and the average electron energy, $\bar{\epsilon}$ involved in calculations over the E/p range <1 V cm⁻¹ torr⁻¹ was low compared with the upper energy limit, ϵ_L



Comparison between measured and calculated D/µ results as a function of E/p, for Ne/10% $CH_4.$

employed. These two factors make calculation of transport coefficients for this mixture sufficiently reliable. Further, the fact that observed results of both drift velocity and D/μ for Ne/10% CH₄ are in good agreement with theoretical predictions confirm the remark made in section 7.2.3, that is, using the cross-section data of Robertson (1972) for neon and Duncan and Walker (1972) for methane in the modified Boltzmann-Holstein formulation allows meaningful prediction of transport coefficients and energy distributions if for Ne/CH₄ mixtures.

7.3.3 Argon/3% carbon dioxide:

Theoretical and experimental D/μ results for this mixture are shown in figure 7.14. Here measured results are systematically higher than theoretical predictions. As discussed in preceding sections, the accuracy of D/μ values depends, not only on the accuracy with which R is measured but also on the accuracy with which D/μ is determined from any R. The error in D/μ at R in the range 0.30 to 0.55, as figure 6.11 shows, is minimal. In fact most of D/μ data point for A/3% CO₂ shown in figure 7.14 were determined from R values in this range. Applying the modified Boltzmann-Holstein equation to determine transport coefficients for A/CO_2 mixture, as discussed in section 7.2.4, has certain limitations. The effect of these is more pronounced when the mean electron energy is in the vicinity of the Ramsauer minimum of the argon cross-section. This effect is clearly exemplified in the drift velocity results for A/10% CH₄ (figure 7.3) and the D/μ results for A/50% CH₄ (figure 7.12). For these reasons one has to consider more basic factors to explain the disagreement between D/μ measured and calculated results for the A/3% CO₂ mixture. One possible explanation is that the carbon dioxide cross-section employed in the calculations

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may be considerably in error thus leading to inaccurate predictions. The poor agreement between drift velocity calculated and measured results for all A/CO_2 mixtures studied, may confirm this.

7.4 Experimental errors

7.4.1 Errors in drift velocity measurements

It was discussed in preceding chapters that the differencing procedure adopted in the present work to measure drift velocity eliminated, to a first approximation, errors due end effects and diffusion. In this section other sources of experimental error will be discussed.

The major error in drift velocity measurements occurs in the scatter of data points (extrapolated peaks). The magnitude of this error was determined by a least-square data fitting procedure similar to that presented in appendix IIIA. Error varied from 0.3% to about 3% (in most cases the error was better than 2%). In addition there may be a systematic error of about 1%. Fluctuation of position of peak due to variation of pulse heights was 0.3%. This was measured using charge pulses ranging from $5 \cdot 10^{-15}$ C (threshold) to $4.2 \cdot 10^{-14}$ C. Error in time calibration was 0.1%. Drift voltages were measured with a digital voltmeter to an accuracy of 0.1 V. Pressures were measured with a gauge with an accuracy (at atmospheric pressure) of about 0.5%. Error in setting drift distance was negligibly small. Therefore an overall error of about $\pm 3\%$ may be associated with the drift velocity values presented in this thesis.

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7.4.2 Errors in D/μ measurements

(i) <u>Current ratio</u>:

As we have seen in the preceding chapter, one of the major factors governing the accuracy of lateral diffusion measurements lies in the current ratio R. Two aspects may be considered here. Firstly, there may be a random error in determining current ratios, R. Secondly, the accuracy of D/μ depends on the value of R at which D/μ is determined. Random error is determined by considering the two modes of operation. A current ratio R may be obtained under some experimental conditions with the amplifier containing the potentiometer (figure 4.15) connected to the central collector (we may refer to this as the normal mode). Another value of R may be obtained, under the same experimental conditions, with the two amplifiers interchanged, i.e. the amplifier with the potentiometer connected to the quadrants (this operation may be referred to as the reverse mode). In the normal mode, if r_1 is the potentiometer reading and R_1 is the corresponding current ratio then, from eqn 5.10,

$$R_1 = \frac{2r_1}{1+2r_1}$$

and in the reverse mode if r_2 is the potentiometer reading and R_2 is the corresponding current ratio then from eqn 5.13,

$$R_2 = \frac{1}{1+2r_2}$$

Under ideal conditions $R_1 = R_2$ and the product r_1r_2 is a constant equal to 0.25. A series of measurements carried out in both modes to verify this, indicated that the deviation from the ideal condition is ± 0.005 . It can be shown that this deviation is equivalent to a deviation of about 1% in R.

As discussed in section 6.3.3, D/μ values measured in the present work depended strongly on R, at R values outside a certain range. The correction required in D/μ due to R was estimated (with respect to values of D/μ at R, 0.5) from a wide range of experimental data (figure 6.11). Three regions of this correction curve may be considered, 0.3 < R < 0.6, R > 0.6 and R < 0.3. In the first region the experimental data, from which the correction factor was estimated, were consistent and showed small variation of D/μ with R over a wide range of D/μ . The experimental data used to estimate the correction factor for D/μ at R > 0.6 and R < 0.3, on the other hand, showed large variations. In estimating the correction required at any R in these regions these variations were averaged and the deviation from the average was determined. This deviation, which was about ±5% is indicated by error bars in figure 6.11.

(ii) Finite size of source-hole:

The effect of this factor was discussed in section 6.3.2. Error due to finite size of the hole was estimated as 1%.

(iii) Error due to mismatch between feedback resistor:

It was determined by experiment that the feedback resistors, R_1 and R_2 , of the two current amplifiers were mismatched by about 0.7%; this error was corrected in the final results.

(iv) Other errors:

These include accuracy of voltage and pressure measurements which were discussed in the preceding section. The total error due to these factors is 0.6%. Estimated overall error applied to measurements obtained at R in the range 0.3 to 0.6 is $\pm 3\%$, and that applied to D/μ values obtained at R values outside this range is between 3% to 8%. Errors are indicated by error-bars in results presented in this thesis.

CHAPTER 8

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<u>CONCLUSIONS</u>

Several offshoots of associated research topics have come to light during the course of the present work. It is unfortunate that serious time limitation prevented detailed investigations to be carried out in these topics. In the following sections these topics, which are of both experimental and theoretical nature, will be discussed briefly together with suggestions on some possible future research.

8.1 Longitudinal diffusion

Although various attempts carried out in the present work to measure longitudinal diffusion coefficients were not successful, they revealed some information and ideas that may be useful for future investigations. Under the conditions at which the present time-offlight system was employed, effect of longitudinal diffusion could clearly be observed, e.g. variation of spread of spectra with pressure; however, it was not possible to quantify this parameter. The main reason for this, as discussed in section 5.3, was that arrival time distributions were dominated by a combined effect of contributions from electronics noise, UV-pulse width and variation of electron flight paths. The use of a cathode pulser in the time-of-flight system made it possible to reduce contribution of UV-pulse width substantially. Nevertheless, because of pressure and geometrical limitations it was very difficult to extract contribution of diffusion from arrival time spectra particularly when a differencing procedure was employed. In the light of the discussion above it may be useful to consider the following broad guide lines in modifying the present system or designing a new system for measuring longitudinal diffusion coefficients. Firstly,

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the length of the chamber may be extended possibly to 25 cm. This enhances the contribution by diffusion to arrival time spectra. Secondly, a section of drift length may be varied to cover distances 10 to 25 cm. This makes possible employing larger length intervals (in the present attempts intervals of 0.5 cm were used), thus enabling variation of longitudinal diffusion effect with length to be more distinct. Thirdly, further research is needed to investigate effect of grids on measurements. In the present attempts two types of grids were used, a stainless steel grid of the type described in section 5.3.2 which had an optical transmission of 50%, and a copper micromesh type (section 4.2.1) with an optical transmission of 42%. The main aim of using small aperture grids was to limit penetration of cathode pulse field into the drift region and thus avoid serious field distortion in the upper boundary of that region. However, employing such grids, as discussed in section 5.3.2, introduced an additional contribution to time-of-flight spectra, i.e. that was due to variation of electron flight path. Although the magnitude of this effect could not be determined, it seemed small. Nevertheless, under conditions at which experiments were carried out this had a serious effect. It is believed that by using longer drift chamber and lower pressures the effect may be less serious. Furthermore, employing low pressures, possibly in the range 10 to 25 Torr enhances contribution by diffusion to arrival time spectra. Enhancement of diffusion contribution by pressure reduction and increase of drift length, together with reduction of combined contribution by non-diffusive factors to arrival-time spectra are advantageous from the data analysis viewpoint. Finally, theoretical predictions of longitudinal diffusion coefficients are really needed for comparison with measurements and to provide a guide for more accurate

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choice of experimental parameters and conditions.

With the advantages outlined in section 5.3.3, the method of overlapping distributions in worth consideration in future research.

8.2 Lateral diffusion

It is recognised that considerable difficulties exist in obtaining reliable D/μ measurements, using the Townsend-Huxley type of diffusion chamber, when the mean electron energy approaches the energy of gas molecules (<0.5 eV). Such difficulties were experienced by Crompton et al., and Warren and Parker (1962). A clear indication of these difficulties may be seen in the disturbingly large variations of published D/μ data obtained in the low energy region below 0.5 eV. In the present work, although great care had been taken in the design and construction of the diffusion chamber, similar difficulties were experienced. The main difficulty encountered during the present measurements arose from an observed behaviour indicating dependence of $D\!/\mu$ values on the current ratio R. This dependence was particularly pronounced in measurements involving low D/μ values, i.e. large R values (>0.6). It is not quite clear whether this dependence had resulted from problems of a similar nature to those experienced by Warren and Parker (i.e. from factors associated with the diffusion chamber), or due to some unknown factors associated with the current measuring system. Perhaps one reason that prevented a decisive answer is the fact that the experimental approach for measuring current ratios is new and experience in using it is very limited. The reproducibility of results in the range of R 0.3 to about 0.55 was good; nevertheless, a number of anomalous observations are left without explanation. Clearly, further research is needed in this area. One disturbing

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feature observed is that D/μ values seem to remain virtually independent of R over a relatively wider range of R below 0.5 than above 0.5. This feature is very puzzling and clearly needs explanation. Explanation of this feature and the D/μ -R dependence are very important in establishing the validity of the current measuring system, used in this work.

8.3 Theoretical calculations and experimental results

From comparisons between experimental drift velocity and D/μ results, and calculations based on available cross-section data the essential conclusion that must be drawn is that further study, both experimental and theoretical, is required. For example, a useful readily available counting gas such as A/10% CH₄ can apparently yield a very wide range of experimental drift velocity results. Theoretically, although it may be possible to reproduce rather accurately electron transport coefficients, from cross-section data, for the individual components of a certain gas mixture, predictions for the mixture itself may not be wholly reliable. Argon/methane and argon/ carbon dioxide mixtures exemplify this. On the other hand, calculations on the neon/10% methane mixture appear to be in good agreement with (limited) observations.

Examination of the argon/methane and argon/carbon dioxide situations shows that two main assumptions made in the present calculations may, under certain conditions, both be violated. Firstly, because of the pronounced cross-section minimum in argon (not exhibited by neon) the inelastic cross-section may not be small compared with the elastic cross-section. Secondly, the asymmetry ratio, as the present calculations clearly show, is not always small compared with unity. The extent

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to which the two term expansion of the energy distribution function is valid in the present situations needs to be examined quantitatively, possibly in the manner in which Milloy and Watts (1977) have examined the validity of the two-term expansion for pure argon. It is hoped that such calculations for the mixtures studied in the present work will be undertaken in the near future. In considering a more basic level reasons for disagreement between theoretical predictions and experimental measurements of drift velocity and D/μ , one can not rule out the possibility that some current cross-section values are considerably in error. The momentum transfer and inelastic cross-sections for both methane and carbon dioxide are still by no means as firmly established as the neon and argon cross-sections.

APPENDICES

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APPENDIX I

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	LISCING OF C	the computer programme used in the numerical
	calc	ulations of transport coefficients
	PROGRAM G2	73/72 OPT=2 20010=+-+/ MANTRAP FTN 4.6+452
1		PRDGPA4 G2(I)PUT, CUTPUT, TAPES=I'NPUT, TAPE6=OUTPUT, 1TAPEJ, TAPE7, TAPE4))I 4 JST 71 F (2043) • EX1 (2048) • EX2 (2048) • EM(56) • SUM(56)
5		1, $X1(24)$, $Y1(24)$, $X2(24)$, $Y2(24)$, $X3(16)$, $Y3(24)$ 2, $A1(24)$, $31(24)$, $G1(24)$, $D1(24)$ 3, $A2(24)$, $32(24)$, $G2(24)$, $D2(24)$ 4, $A3(16)$, $J3(16)$, $G3(16)$, $D3(16)$ 5, $DY(24)$, $UE(132)$, $DY3(36)$, $dE3(126)$
10		6, AAR(42), BAR(42), CAR(42), DAR(42), XAR(42), YAR(42) 7, DY 42(42), WEAR(306))I HE 151) NK(11), EHK(11), RATK(11), DPK(11), DBYHUK(11), WK(11) REAL KT CALL KT // NK(11), EHK(11), RATK(11), DPK(11), DBYHUK(11), WK(11)
15	200	00 200 1=1,24)Y(1)=1.0 COUTIVE 00 210 1=1,16 07 210 1=1,16
20	210	00 ITINJE 00 ITINJE 00 ITINJE 0 YAR(I)=1.J
25	19	<pre>Head(3,*)(x1(1),I=1,24),(Y1(1),I=1,24) Head(3,*)(x2(1),I=1,24),(Y2(1),I=1,24) Read(3,*)(x3(1),I=1,24),(Y3(1),I=1,24) Read(9,*)(x3(1),I=1,16),(Y3(1),I=1,16) Read(4,*)(xA{(I),I=1,42}),(YAR(I),I=1,42) </pre>
30		CALL E33LF1(24,X2,Y2,OV,S,A2,B2,G2,D2,WE) CALL E33LF1(24,X1,Y1,OY,S,A1,B1,C1,D1,WE) CALL E33LF1(16,X3,Y3,DY3,S,A3,B3,C3,D3,WE3) CALL E33LF1(16,X3,Y3,DY3,S,A3,B3,C3,D3,WE3) CALL E33LF1(42,XA5,Y3,F,DYAR,S,AAR,BAR,CAR,DAR,WEAR) SOTO 330
35		CALL P4PER(1) GALL F3A15 GALL H3P(0.0,0,4.0,0.0,8.0) GALL AXES GALL PTPLOT(X1,Y1,1,24,34)
40		GALL RSGDRV(X1,A1,1,24) GALL RSGDRV(X1,A1,1,24) GALL RYFC(0,1,4,0,0,0,0,8,0) GALL AXES GALL PTPLOT(X2,Y2,1,24,34) GALL PTPLOT(X2,Y2,1,24,34)
45	300	CALL G E ID CONTINIE EBYP=0.8 F2=0.75 F3=0.0
5)		F4=0.0 TE1P=2JJ 5LIX=5.0 00 430 INDEX=7.11 TLIXE2*FT4DEX
55		A=442*E370**2 PI=3.1415326 KT=3.85146-04*TEMP 7LIM=ELIM/KT JZ=ZLIM/FLOAT(MLIM)
69		K=0 IF(I)05X.ST.7) G010 7 ZME=4.*E3YP(3.*KT) 00 5 I=1.4LI1 Z=F1 J4I(1)*0Z
65	57	<pre>IF (1/21E.GE.600.)F(I)=(2/SQRT(PI))/(EXP(6C0.)*ZME**(3/2)) IF(2/21E.LT.600.)F(I)=(2/SQRT(PI))/(EXP(Z/ZME)*ZME**(3/2)) GOITINIE GOITINIE LF(CLUCK.F0.Z) GOID 100</pre>
70		PEAD(7)F PD=1 D0 110 T=2-MUTM-2
75	110)=1LIM-I+2 F(J)=F(J/2) CC/ITIN/E F(1)=F(2)/2 D9_120_7=4_MLIM_22
80	129 100	PD=1

	PROGRAM G2	73/72	OPT=2 ROUND=+-*/ MANTRAP FTN	4.6+452
	6	K=K+1		
85		SG=0 SF=C SZM=D		
		SDP=)		
90		1212=IFIX(). 1212=IFIX(). 51=0 52=0	377(KT*0Z)) .57(KT*0Z))	
95		00 20 J=1,HLI IZD=1LI1-J+1	IM .	
		Z D=FL OAT(IZO) ED=Z)*:T IF(E).LE.3.37	*DZ 7) GOTO 230	
100	220	$\vec{I} = \vec{I} + 1$	CIN GCT0 220	
		T = T - 1 H = T 0 - X1 (T)		
105	230	1H_1=0.01*(0) IF(E).LE.0.3 IF(E).LE.0.10	(I)*H**3+C1(I)*H**2+B1(I)*H+A1(I)))	
	240	$\hat{I} = \hat{I} + 1$ IF(E).GT.X2()	()) GCT0 240	
110		I=1-1 H=ED-X2(I)		
	250	1412=0.01+() IF(E).LE.0.1	(I)+H++3+C2(I)+H++2+B2(I)+H+A2(I))) 01I2=0.0	
115		S1=S1+F(IZD) S2=S2+F(IZD)	0H12+Z0+DZ 0H12+Z0+DZ	
	20	$E_{X2}(I_{7}) = S1$ $E_{X2}(I_{7}) = 32$		
4.2.0	20	JE 101 = 1LIM - I		
129			17) /ENDI=1 12 TAN 16ND 2-1	
		10 31 J=1 JE	101	
125		F()_1.9T.ML		
	30	CONTINUE 00 40 1=1.1F	102	
130		JI2=1+5Z_2 TEC172-0T-X11		
100	40	EX2(])=EX2(])	-EX2(J12)	
		10 50 1=1,4L1 Z=FL)AT(I)+0	м	
135		E=?*KT (N=(-13.75*E	65)/10	
		IF(E.LT.2.4) IF(E.LT.1.3)	IN=(20+E-16)/10 IN=1.0	
140		IF(E.LT.J.45) IF(E.LT.0.J0	0N=(1.9+11.74*E**9.333)/19)0N=0.12	
		IF(E.LE.0.01)	ŠOTO 270	
	260	L=L+1 IF(E.GT.X3(L)) GOTO 260	
145		L=L-1 H=E-X3(L)		
	270	IF(E.LT.J.3) IF(E.GE.9.3.4	QH=].0625/SQRT(E) \ND.E.LT.8.0) QH=0.369*E**0.975	
150		IF(E.GE.8.3) 7A=1.52*E/11	14=2.8/S1RT(8.0/E)	
		IF(E.GT.4.)) IF(E.LT.J.02)	GOTO 275 DA=3•1*(3•28+(0•02−E)*100•)	
		IF(E.LT.).)2	G0T0275	
155	274	L=L+1 IF(E.GT.XAR(.))6010 274	
		L=L-1 H=E-X43(L)		
160	275	1A=2.1*.(DAR (1 CONTINUE	.)*H**3+GAR(L)*H**2+BAR(L)*H+AAR(L))	
		IF(E.LT.).01)	GOTO 230 74*E+2,54*E**1,5)	

	1	PROGRAH G2	7	3/7	2	OPT=2	300	10=+•	*/	HANTRAP	FTN	4.6+452
	165	230	IF(E.LT TH==F2* IF(F(I) SUMEX=J B=1+SUM C=1+A/	-1/1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-)1) 5+F* 57 7 1 7 7 1 7 7 1 1 7 7 1 1 1 1 1 1 1 1 1 1 1 1 1	942C=1 3*94207 9420755 EXP(609 2*(5X1) 7*T4*F THD)	184+F+ 180NF+ 1))F5 1))F5	4*Q' (1-F (I)= X2()	1/29 2-F	8+(1-F2-F3-F4) 53-F4)*9A EXP(600.)	* QA / 40	
	175		SG=SG+G IF(SG+G IF(SG+L IF(SG+L)	* ETET.)).)).)).)F(I)=)F(I)=)P=P+3)P=P+3	1/P0 1/P0 1.T(7)/E))*0		500.) 56) (P(500.) (P(56)		
	189	50	SF=SF+3 SZ1=SZ1 SW=S1+5 SD2=S3P SRAT=S2 C01TIN1	127 +Z7 +Z7 +27 +27 +27 +27 +27 +27 +27 +27 +27 +2	(7) 302 • 23 • 76	*F(I)*C T(Z)*F(.76*SOF *KI*SOF *EBYP*S	1)*0 T (KT T (KT SQRT(Z) * 7) * Z Z) * 1	F(1)	()*G*OZ/THO ()*OZ/THO)*G*OZ/THD		
	185	1.	P0=P ZM=SZM/ W=SM/SF DP=SDP/ DPYMJ=) VAT=SP	SF SF	W/E	BYP)						
	199	55	00 05 1 F(I)=F(C0)TIN) EM(K)=Z CU1(K)= IF(K,LE		SF	n 10.6						
	195	390	18(1105) 18(K.=() 3140=() 18(310) 98(11-0) 88(11-0) 88(11-0)	X) = 2 -33(-57)	x SU1 • 0•	010 330 (K)-SU 901) GC	1(K-2)TC 6	2))+)	A3S	(SUM(K)-SUM(K-	4)))/5	UM(K)
	200		EPR(IN) RATK(I) OPK(IN) OBYMIK(WK(I)OS		= EM) =R = DP E X) H	(K) AT = 08YMU						
	205	400 50	CONTIND KLIMEN IRITE(5 FORMAT(D0 95 I)) EL ,//	IM, MLI , F5.2,	1,F2	EBY ,5X	, F5.	.2,5X,F6.3,//)		;
	219	40 90	K=KLIM- NRITC(6 FORMAT(CONTINU NRITE(6	7+1 131 E 15) K, 4X,	EM(K),5 F7.4,45	SUM (K (,F8,	() (4)				
	215	35	F0-411)0-33 E=FL)AT Z=57(T T=1FIX(77,	F7. 5. * J.	5,3X,F; 05	. 3, 2	λ,F	7.3:	9X,F6.3,//)		
-	220	17 98	SPECES IF(E.GE HRITE(6 FORMAT(COUTINU	EL, 17	7)* IM))E,	F(I)/K1 SPEC=(SPEC X,E13.3).0 353)					
	225	36	WRITE(6 FORMAT()0_410 HLIME2* MRITE(6	, J5 //) I1 I1 I1 I) E X= DEX) ML	7,11 IN,1K()	NDEX	(),E'	15 (]	INDEX), RATK(IN	DEX),	
	230	9) 410	1)P:((IN) FORMAT(1F7.3,4% CONTINU ST)P	EX) F7	, 0) , X , 3)	YMUK(I) 15,4X,F	7.4;	4X,1	(IN) -8.	DEX) 4,4X,F7.3,4X,		•
	235		END									

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APPENDIX II

<u>Measurements of small currents using an operational amplifier and phase-sensitive detector</u>

1. Principle of method



The basic principle of the method is very simple. The small, alternating current to be measured, i, flows into the 'virtual earth' of an operational-feedback current-sensitive amplifier, as shown in Fig. 1. The amplifier output, an alternating voltage iR, is detected by a phase-sensitive detector whose reference signal is derived from the same frequency source that produces i. The noise bandwidth of the system is determined by the final integrating circuit of time constant T.

By employing a PSD with maximum sensitivity 1 μ V, then with $R = 2.10^9$ ohms the current sensitivity of the system should be 5.10^{-16} A. However noise from the operational amplifier and thermal noise from the resistor prevent this sensitivity being achieved; the situation is discussed in more detail below. Also considered below are factors which determine the frequency at which the system should be operated and also the gain stability.

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In reality the operational amplifier has a finite gain, a finite bandwidth and a finite input resistance. Further there must always be associated with the input a capacitance C (perhaps a few tens of picofarads). It is necessary therefore to consider the real circuit performance in more detail.

The complex, frequency dependent gain of the operational amplifier may be written in the form:

$$A = \frac{A_0}{1 + j f/f_0}$$

where A_0 is the DC gain and A_0f_0 is the so-called gain-bandwidth product; both A_0 and A_0f_0 are quoted by operational amplifier manufacturers. Analysis of the circuit shown in Fig. 2 then shows that the output voltage v and the input current i are related by the expression:

$$-\frac{iR}{v} = 1+p$$

where $p = \frac{1}{A_o} \left\{ 1 + \frac{R}{R_i} - \frac{w^2}{w_o w_R} + j \frac{w}{w_o} \left(1 + \frac{w_i}{w_R} + \frac{w_o}{w_R} \right) \right\}$

In this expression $w_i = 1/R_iC$ and $w_R = 1/RC$.

It is now worth considering actual values. The high quality operational amplifier (Type OP-15G) used in the present work was chosen primarily for its low noise and high input impedance. From the manufacturer's specifications

 $A_{o} = 106 \text{ dB} = 2.10^{5}$ $A_{o}f_{o} = 5.4 \text{ MHz} \qquad \text{Therefore } f_{o} = 27 \text{ Hz}$ $R_{i} = 10^{12} \text{ ohms}$

The feedback resistor R is 2.10⁹ ohms and the total input capacity may be estimated at about 20 pF. Thus $f_R \sim 4.0$ Hz.

Clearly as far as gain stability is concerned, only the third term in the expression for p need be considered. That is:

$$p \simeq \frac{f^2}{A_0 f_0 f} = \frac{f^2}{21.6.10^6}$$

Thus if we require that p should be less than say 10^{-3} then f should be less than about 147 Hz.

It is shown below that a rather lower limit for the operating frequency is imposed by the necessity of preventing parasitic oscillation.

3. <u>Noise performance</u>

The ultimate current sensitivity of the system is determined by the noise generated by the operational amplifier and the thermal noise generated by the feedback resistor.

Consider first the basic operation of a phase-sensitive detector. In effect it is a modulator; an input signal v cos (wt + \emptyset) is multiplied by a constant amplitude reference signal cos w_Rt. That is, the output from the modulator is given by

$$v \cos(wt+\phi) \cos w_{R}t = \frac{v}{2} \left\{ \cos[(w+w_{R})t+\phi] + \cos[(w-w_{R})t+\phi] \right\}$$

After the first, 'high frequency' term has been filtered out this reduces to

$$\mathbf{v}_{\mathbf{m}} = \frac{\mathbf{v}}{2} \cos \left[(\mathbf{w} - \mathbf{w}_{\mathbf{R}}) \mathbf{t} + \boldsymbol{\emptyset} \right] = \frac{\mathbf{v}}{2} \cos \left(\mathbf{w}_{\mathbf{m}} \mathbf{t} + \boldsymbol{\emptyset} \right)$$

Clearly when $w \equiv w_R$, as for the required signal input, then

$$v_m = \frac{v}{2} \cos \emptyset$$

which is the average DC output read by the output meter. Unwanted signals, $w \neq w_R$, yield an AC output whose average is necessarily zero. The amplitude of these unwanted AC output components may be attenuated by means of an integrating circuit, see Fig. 1. If v_o is the integrating circuit output then clearly

$$\left|\frac{v_{o}}{v_{m}}\right|^{2} = \frac{1}{1 + (w_{m}T)^{2}}$$

where T is the integrating circuit time-constant.

Now consider the system noise, and suppose that this may be represented by a current generator, at the input, whose mean square value per unit bandwidth is (di_n^2/df) . Because of the action of the PSD and integrating circuit on each of the noise sinusoids, the resultant output of the system is equivalent to an input noise generator of mean square value i_n^2 given by

$$i_{n}^{2} = 2 \int_{0}^{\infty} \left(\frac{di_{n}^{2}}{df} \right) \frac{df_{m}}{1 + (w_{m}T)^{2}}$$

The factor 2 appears because an AC signal of frequency w_m is generated by the modulator for noise inputs of frequency $(w_R + w_m)$ and $(w_R - w_m)$.

If we assume, reasonably, that (di_n^2/df) is constant over a bandwidth of the order 1/T then

$$i_{n}^{2} = 2 \left(\frac{di_{n}^{2}}{df} \right) \frac{1}{2\pi T} \int_{0}^{\infty} \frac{d(w_{m}T)}{1 + (w_{m}T)^{2}} = 2 \left(\frac{di_{n}^{2}}{df} \right) \frac{1}{4T}$$

That is, the equivalent noise bandwidth of the integrating circuit is 1/4T.

Now for thermal noise from a resistor R at temperature $T_{\mbox{e}}$

$$\begin{pmatrix} \frac{\mathrm{di}_{\mathbf{n}}^{2}}{\mathrm{df}} \\ R \end{pmatrix} = \frac{4\mathrm{kT}_{\dot{\mathbf{e}}}}{\mathrm{R}}$$
Thus we can write $\begin{pmatrix} \frac{\mathrm{di}_{\mathbf{n}}^{2}}{\mathrm{df}} \\ R \end{pmatrix} = \frac{4\mathrm{kT}_{\mathbf{e}}}{\mathrm{R}} + \begin{pmatrix} \frac{\mathrm{di}_{\mathbf{n}}^{2}}{\mathrm{df}} \\ R \end{pmatrix}_{\mathbf{A}}$

where the second term represents the noise from the operational amplifier. For the amplifier employed the manufacturer quotes the rms noise as 10^{-2} pA/ \sqrt{Hz} . Hence using R = 2.10⁹ ohms, at room temperature,

$$\left(\frac{\mathrm{di}_{n}^{2}}{\mathrm{df}}\right) = 8.10^{-30} + 10^{-28} \approx 10^{-28}$$

With an integrating time constant of 3.0 s we then have

$$i_n = \left(\frac{di_n^2}{df}\right)^{\frac{1}{2}} \frac{1}{(2T)^{\frac{1}{2}}} \simeq 4.10^{-15} \text{ A}$$

4. <u>Stability against oscillation</u>

Because of unwanted, positive feedback the system described above is susceptible to instability. This may be simply understood by considering the effective input admittance of the system, Fig. 2.

$$Y = -\frac{i}{v/A} = A \frac{1+p}{R}$$

For simplicity of algebra suppose that $p \approx 0$ (a complete analysis does not change the essential result). Then the input inpedance is $Z = R/A = R (1 + j W/W_0)/A_0$

It can be seen that the input appears as a resistance R/A_0 in series with an effective inductance $L = R/w_0A_0$. With the present system L = 127 H. This very large inductance, in series with a relatively low resistance R/A_0 , may resonate with the small input capacitance C. The resonant frequency, with C = 20 pF, is approximately 3kHz as indeed observed.

Complete immunity to instability can be achieved, at the expense of frequency response, by introducing an extremely small amount of capacitive feedback C_f in parallel with the resistive feedback. The main effect of this is to place a very large capacitance A_oC_f across the input. In the present system $C_o = 1$ pF so that $A_oC_f = 0.2 \mu$ F. This completely inhibits any tendency to oscillate.

The result of a more detailed analysis of the situation is summarised for interest in Fig. 3 which represents the equivalent circuit of the input to the system.



The disadvantage in using some capacitive feedback is that the operational amplifier output becomes somewhat dependent upon the value of C_{f} . If two systems are to be used differentially, as in the present work, then either the C_{f} s must be accurately known or the dependence must be made very small.

It is easy to see that, to first order, the operational amplifier

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output is given by

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$$v = \frac{iR}{\sqrt{1 + (w/w_f)^2}} \quad \text{where } w_f = 1/RC_f$$

With $R=2.10^9$ ohms and $C_f=1$ pF then $f_f=w_f/2\pi=80$ Hz. By operating at f=10 Hz, the square root term above differs from unity by less than 1%. Thus assuming that the two C_f values in the two systems are roughly equal, the difference in the two system sensitivities is quite negligible.

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Reduction in the operating frequency below 10 Hz is not only unnecessary; it could be disadvantageous since amplifier noise increases with decreasing frequency.

APPENDIX IIIA

Listing of the least square data fitting programme

22 DIM X(1222. 33 DIM Y(182) 62 LET . R=2 " 72 LET 3=2 80 LET. T=2 35 READ K 98 FOR N=1 TO K 100 READ X(N);Y(N) 110 LET P=P+X(W) 122 LET Q= Q+Y(N). 132 LET R=2+X(N)+X(N) 142 LET S=5+Y(N)+Y(N) 152 LET T=T+X(N)+Y(N) 162 NEXT N 172 LET. D=K+R-P+P. 138. LET E= (Q+Q+R-2+5+P+Q+K+1+7)/D 198 LET F=SUR((S-E)/(K-2)) 222 PPINT (K+T-P+Q)/D, F+SQR(K/D) 212 PRINT (R+Q-P+T)/D, F+SQR(R/D) 222 END 230 D414 5 242 DETA .5, 154. 20, 1.5, 172.1, 2.5, 135.99, 3.50 221.97, 4.5, 213.21 252 6676 22 READY . AUN 15.977 148.2335 .42557345-1 RUN

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APPENDIX IIIB

REFERENCES

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REFERENCES

Alison, W. J., and Draper, J. E., Nucl. Instr. and Meth., 35 (1965) 155. Barbieri, D., Phys. Rev., 51 (1951) 653. Bortner, T. E., Hurst, G. S., and Stone, W. G., Rev. Sci. Instr., 25, 2 (1957) 103. Bowe, J. C., Phys. Rev., 117 (1960) 1411. Bowman, C. R., and Gordon, D. E., J. Chem. Phys., 46, 5 (1967) 1878. Bradbury, R. A., and Nielson, N. E., Phys. Rev., 51 (1937) 69. Breare, J. M., and Von Engel, A., Proc. Roy. Soc. A, 282 (1964) 390. Bredford, D. K., J. Phys., E:3 (1970) 77. Brode, R. B., Rev. Mod. Phys., 5 (1933) 257. Carceres, E., Goni, A. J., and Alvariz Rivas, J. Phys., E:7 (1974) 178. Charpak, G., Sauli, F., Sault,於,於., and Duinker, W., Nucl. Instr. Meth., 108 (1973) 613. Christophorou, L. G., and Christodoulides, A. A., J. Phys., B:2 (Proc. Phys. Soc. London) 2 (1969) 71. Crompton, R. W., Aust. J. Phys., 22 (1969) 715. Crompton, R. W., Elford, M. T., and Gascoigne, J., Aust. J. Phys., 18 (1965) 409. Crompton, R. W., and Jory, R. L., Aust. J. Phys., 15 (1962) 451. Cottrell, T. L., and Walker, I. C., Trans. Faraday Soc., 61 (1965) 1585. Duncan, C. W., and Walker, I. C., Trans. Faraday Soc., 68 (1972) 1514. Duncan, C. W., and Walker, I. C., Trans. Faraday Soc., 70 (1974) 577. Duncan, R. A., Aust. J. Phys., 10 (1957) 57. Elford, M. T., Aust. J. Phys., 19 (1966) 629. El-Hakeem, N. S., and Mathieson, E., 3rd. Int. meet. on Prop. and Drift Chambers, Dubra, USSR, June (1978). Engelhardt, A. G., and Phelps, A. V., Phys. Rev. 133:A (1964) 375.

English, W. N., and Hanna, G. C., Canad. J. Phys., 31 (1953) 768. Frost, L. S., and Phelps, A. V., Phys. Rev., 127 (1962) 1621. Frost, L. S., and Phelps, A. V., Phys. Rev., 136, 6A (1964) 1538. Hake, R. D., and Phelps, A. V., Phys. Rev., 158 (1967) 70. Harris, T. J., M.Sc. Thesis, University of Leicester (1972). Herbst "Electronics for Nuclear Particle Analysis", Oxford University Press (1970). Holstein, T., Phys. Rev., 70 (1946) 367. Hurst, G. S., and Parks, J. E., J. Chem. Phys., 45 (1966) 282. Hurst, G. S., O'Kelly, L. B., Wagner, E. B., and Stockdale, J. A., J. Chem. Phys., 39, 5 (1963) 13. Huxley, L. G., and Crompton, R. W., "Atomic and Molecular Processes", Academic Press, N.Y. (1962). Huxley, L. G. H., and Crompton, R. W., "Diffusion and Drift of Electrons in Gases", John Wiley, N.Y. (1974). Kayat (1978) - Private Communication. Locus, J., Int. J. Elect., 27 (1969) 201. Loeb, L. B., "Basic Processes of Gaseous Electronics", University of California Press, Berkley (1955). Lowke, J. J., Aust. J. Phys., 15 (1962) 39. Margerians, H., Phys. Rev., 69 (1946) 508. Milloy, H. B., and Robertson, A. G., Aust. J. Phys., 30 (1977) 51. Milloy, H. B., Crompton, R. W., Rees, J. A., and Robertson, A. G., Aust. J. Phys., 30 (1977) 61. Moruzzi, T. L., Rev. Sci. Instr., 38, 9 (1967) 1284. Nelson, D. R., and Davis, F. J., J. Chem. Phys., 51 (1969) 2322. O'Malley, T. F., Phys. Rev., 130 (1963) 1020. Pack, J. L., and Phelps, A. V., Phys. Rev., 121 (1961) 798. Pack, J. L., Voshall, R. E., and Phelps, A. V., Phys. Rev., 127, 6 (1962) 2084. Palladino, V., and Sadoulet, B., Nucl. Inst. Meth., 128 (1975) 323.

Parker, J. H., and Warren, R. W., Rev. Sci. Inst., 33 (1962) 948.

Phelps, A. V., Rev. Mod. Phys., 40, 2 (1968) 399.

Phelps, A. V., Phys. Rev., 117 (1960) 470.

Pollock, W. J., Trans. Faraday Soc., 64 (1968) 2919.

Robertson, A. G., J. Phys. B: At. Mol. Phys., 5 (1972) 648.

Robertson, A. G., Aust. J. Phys., 30 (1977) 39.

Schultz, G., and Gresser, J. Nucl. Inst. Meth., 151 (1978) 413.

Townsend, J. S., "Electricity in Gases", Oxford University Press (1914).

Tyndall, A. M., Starr, L. H., and Powell, C. F., Proc. Roy. Soc. A:121 (1928) 172.

Uman, M. A., Phys. Rev., A:133 (1964) 1266.

Van de Graaff, R., and Tyndall, A. M., Phil. Mag., 6 (1928) 210.

Wagner, E. B., Davis, F. J., and Hurst, G. S., J. Chem. Phys., 47, 9 (1967) 3138.

Warren, R. W., and Parker, J. H., Phys. Rev., 128 (1962) 2661.

N.S. EL-HAKEEM. Ph.D. Thesis. 1978.



ELECTRON DRIFT AND DIFFUSION IN COUNTING GASES
. Nasreldin Salim El-Hakeem

ABSTRACT

An experimental system has been designed with a twofold objective. The system, which has a variable drift length, has been used to measure, for a range of counting gases, drift velocities and longitudinal diffusion coefficients employing the time-of-flight method, and lateral diffusion coefficients using the Townsend method. Several problems have been encountered during the work, these requiring continued modification to be carried out on the system. A detailed description is given of the system and its stages of development.

Attempts to measure longitudinal diffusion coefficients were not successful and possible reasons are fully discussed.

A modified Boltzmann-Holstein equation has been employed with published cross-section data to calculate numerically the electron energy distribution, and hence electron transport coefficients, in the gas mixtures studied, at non-ionising field values. The Boltzmann-Holstein equation is discussed from first principles and the method of numerical solution is explained. Good agreement has been found between calculations and measurements of drift velocities for methane and a mixture of neon/10% methane and of D/ μ for Ne/10% CH4. Predictions for argon/methane and argon/carbon dioxide mixture are less accurate; possible reasons are discussed.