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Title ELECTRON DRIFT VELOCITIES IN HYDROGEN AND DEUTERIUM

Abstract approved

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The drift velocity of electrons in pure hydrogen, in pure deuterium, and in mixtures thereof, has been observed at low pressures using the following pulse technique for these gases for the first time.

Plane parallel electrodes of a known separation and immersed in the gas to be studied are connected in series with a resistor and a source of potential. Ultra-violet light from a spark of very short duration is allowed to fall on the cathode, and the resulting pulse of photoelectrons of correspondingly short duration traverses the gap between the electrodes to the anode, where it is collected. The associated current transient displayed on an oscilloscope gives the electron transit time. The electron drift velocity is determined directly from the above experimental parameters. Standard ultra-high vacuum techniques are employed to ensure high gas purity.
The drift velocities obtained are in good agreement with the previously reported measurements of Bradbury and Nielsen and of Pack and Phelps for hydrogen and of Pack, Voshall and Phelps for deuterium. Data for mixtures of hydrogen and deuterium have not been published hitherto.
ELECTRON DRIFT VELOCITIES IN HYDROGEN AND DEUTERIUM

by

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To Dr. David S. Burch, my major professor, I am indebted for having suggested the present study and for having lent the drift tube and light source which were employed.

Stevens P. Tucker

Corvallis
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ELECTRON DRIFT VELOCITIES IN HYDROGEN AND DEUTERIUM

I. INTRODUCTION

Heretofore no measurements of electron drift velocities in either hydrogen or deuterium have been reported in which the pulse technique introduced by Hornbeck (14, p. 297; 15, p. 374) has been employed. The best measurements of drift velocities in hydrogen were those of Bradbury and Nielsen in 1935 (1, p. 388) and those of Pack and Phelps in 1960 (18, p. 798), both of which made use of an electric shutter, while the only measurements in deuterium were those of Hall, made in 1955 (11, p. 468) using an indirect magnetic deflection method which demanded the assumption of a particular electron energy distribution function. The present measurements of drift velocities in hydrogen and deuterium thus serve as a direct check on the electron drift velocity data of Hall for deuterium and, incidentally, on the previously reported data for hydrogen. In addition drift velocity data are given for various mixtures of hydrogen and deuterium.

Although the velocities of electrons in an electric field in gases at low pressure have been studied both theoretically and experimentally for some fifty years, the experimental measurements of electron drift velocities in hydrogen in particular were not sufficiently accurate to allow the confident making of theoretical tests
until the work of Bradbury and Nielsen. Indeed, since the early 1930's electron drift velocities have been measured with considerably greater confidence than they can be calculated. This is because, as we shall show, the calculation of electron drift velocities demands a knowledge of the exact electron energy distribution, which is not known. (In this connection see References 2, p. 51; 8, p. 96; 13, p. 233.)

Nevertheless, it is not difficult to derive simple theoretical expressions which yield drift velocities in fair (twenty percent or so) agreement with experiment. On the following pages will be presented briefly what has come to be known as the Compton theory of electron mobilities (5, p. 204-221). Before detailed development of the Compton theory, however, it is instructive to consider what might be called a "most naive" derivation of the relationship between the drift velocity of an electron in an electric field and $E/p$, the ratio of electric field strength to gas pressure. Let $L$ be the mean free path of the electrons, and consider it to be a constant for the present. Let $u$ be the average velocity of thermal agitation of the electrons. Then the average time necessary for an electron to travel the distance $L$ is $T = L/u$. If it is assumed that the electrons start from rest with respect to the field direction after each collision, then the average distance moved by an electron in the field direction is $S = \frac{1}{2} aT^2$, where $a$ is the acceleration of the electron.
due to the presence of the electric field $E$; that is, $a = eE/m$, in which $e$ is the electron's charge and $m$ its mass. Substitution of the expressions for $a$ and $T$ into that for $S$ gives

$$S = \frac{1}{2}(eE/m)(L^2/u^2).$$

But the drift velocity is $v_d = S/T$, giving

$$v_d = \frac{1}{2}(eE/m)(L/u) \quad (1)$$

But it is known that $L \sim 1/p$, or $L = b/p$, where, as we shall see, $b$ may or may not be constant. It is therefore possible to write

$$v_d = \frac{1}{2}(eb/mu)(E/p) \quad (2)$$

At one time it was fashionable to consider the mobility, $\mu$, of electrons, i.e. to consider $\mu = v_d/E = \frac{1}{2}(eb/mu)(1/p)$ in the case of our simple model. However, at a very early date it was found that $\mu$ is not proportional to $1/p$ but is, rather, a function of $E/p$. In other words $b = b(E) \neq$ constant as was assumed above. For this reason $\mu$ is no longer calculated for electrons. Instead, the usual procedure is to determine — either theoretically or experimentally — $v_d$ as a function of $E/p$.

Now the model considered so far does not take into account the persistence of directed velocity or the distribution of mean free paths and velocities, and it precludes the calculation of electron velocities among molecules of more than one type. These factors were taken into account by Langevin (16, p. 245) and by Compton.
Compton obtained for the mobility of a carrier (subscript 1) in a gas of molecules (subscript 2) the following expression (5, p. 218):

\[
\mu_{12} = 0.85 \frac{eL}{m_1 u_1} \left[ 1 + \frac{W_2 m_1}{w_1 M_2} \right]^2
\]

(3)
in which \( L \) is the average kinetic theory mean free path for electrons, \( u_1 \) is the average velocity of thermal agitation of the electrons, and \( w_1 \) and \( W_2 \) are average energies. If we assume \( w_1 > W_2 \) and \( M_2 \gg m_1 \), which is reasonable if the carrier is an electron, the mobility becomes \( \mu = 0.85 \frac{eL}{mu} \) upon dropping the subscripts.

The drift velocity is then given by

\[
v_d = 0.85 \frac{eL}{mu} E = 0.921 \left( \frac{eL}{mC} \right) E
\]

(4)
where \( E \) is the electric field and \( C \) is the root mean square electron velocity. This differs from the simply derived expression (1) only with respect to the numerical multiplier. We now assume \( L \) to be constant, leaving \( u \) unspecified at this point. The average time between impacts is then \( T = L/u \). In this time, on the average, the electron drifts a distance \( S = v_d T = 0.85 \frac{eL^2}{mu^2} E \) in the field direction. In electron-volts, \( w \), the average electron energy is given by \( ew = \frac{1}{2}(1.18 \text{ mu}^2) \). Therefore, in terms of the electron energy, \( w \), its advance in the electric field direction is
S = 0.502 L^2 E/w.

Cravath (6, p. 248) has shown that for ions of mass \( m \) in elastic collisions with neutral spherical molecules of mass \( M \) obeying a Maxwellian energy distribution, the average fraction of average energy lost per collision is

\[
f = \frac{8}{3} \frac{M m}{(m+M)^2 (1 - W/w)}
\]  

(5)

\( W \) is the molecule energy given by \( eW = 3/2 kT \). For \( E/p \gtrsim 0.1 \), \( w >> W \), and \( W \) may be neglected. Also, if the ions are electrons, \( M >> m \), making \( mM/(m+M)^2 \sim m/M \).

Therefore, making these approximations for electrons, we have

\[
f \sim \frac{8}{3} \frac{m}{M}
\]  

(6)

One can then express in the following way the manner in which the electron energy, \( w \), measured in electron volts, changes as the electron moves in the electric field:

\[
e \frac{dw}{dx} = eE \frac{dx}{S} - \frac{few}{dx/S}
\]  

(7)

where \( dx/S \) is the number of impacts per length of path \( dx \) in the field direction. If we do not make the approximation for \( f \) which assumes \( w >> W \) and take \( f = 8/3 \frac{m}{M}(1 - W/w) \) and \( S = 0.502 L^2 E/w \), we obtain for the rate of change of electron energy in the field direction

\[
\frac{dw}{dx} = E - 5.3 \frac{mw}{M} \frac{w-W}{L^2 E}
\]  

(8)
The terminal energy of the electrons is obtained by setting $dw/dx = 0$.

Upon doing this and solving for the terminal energy, $w_t$, it is found that

$$w_t = W/2 + \left(\frac{W^2}{2} + ML^2E^2/5.3m\right)^{1/2}$$  \hspace{1cm} (9)

$w_t$ is related to the root mean square velocity $C$: $ew_t = \frac{1}{2}mC^2$.

Solving for $C$ and using (9) for $w_t$, we find

$$C = \left[(2e/m)(W/2 + \sqrt{L^2ME^2/5.32m + W^2/4})\right]^{1/2}$$\hspace{1cm} (10)

This is simplified if we assume, as we may for electrons, that $w \gg W$:

$$C = \left[(2eLE/2.31m)(M/m)^2\right]^{1/2}$$\hspace{1cm} (11)

We are now in a position to substitute (11) into the basic drift velocity equation (4):

$$v_d = 0.921 eLE/mC = 0.921 (2.31/2) (e^2/m^4) [(LE)^2/M^4]$$\hspace{1cm} (12)

If we again write $L = b/p$, (12) becomes

$$v_d = 1.07 [(be)^2/m^4] [(E/p)^2/M^4]$$\hspace{1cm} (13)

It is seen that to the extent $b$ is constant the relationship between $v_d$ and $E/p$ is parabolic. Furthermore, $v_d$, is proportional to
1/M^4; i.e. one should expect \( v_d \) to decrease as the mass of the gas molecules is increased. In order to use (12) one must employ experimentally determined values of \( L \).

By integrating (8) it is possible to determine, within the limitations of the Compton theory, of course, the distance \( x \) needed for the average electron to reach the fraction \( g = w/w_t \) of its terminal energy \( w_t \). This distance is found to be

\[
x = \frac{1}{g} \left[ \frac{1}{2(5.32)^2} \right] \frac{1}{(M/m)^2} L \log \left[ \frac{(1+g)}{(1-g)} \right]
\]  

(14) (17, p. 224-225). Expression (14) is of use in the determination of the minimum allowable experimental drift distance as will be shown in Part III.

It must be remembered that the relatively simple theory outlined is not only based on an arbitrarily chosen energy distribution, in this case Maxwellian, but is in addition based on the assumption that only elastic collisions take place. Despite its shortcomings, however, (12) in conjunction with measured values of \( L \) does yield the general trend of the function \( v_d' = v_d(E/p) \). (See reference 1, p. 342.)
II. THE EXPERIMENTAL METHOD

The method used to obtain the electron drift velocities is essentially the same as that described by Hornbeck (15, p. 374) and provides a direct time-of-flight measurement (see Figure 1). Plane parallel electrodes immersed in the low pressure gas to be studied (p \approx 20 \text{Torr}) are separated by a distance of about one centimeter and have a known potential difference. Light from a spark discharge produces a short pulse of photoelectrons at the cathode of the experimental tube, and the resulting current transient is observed on an oscilloscope. The light pulse duration is approximately 0.2 microseconds, giving a pulse of photoelectrons of about the same length. As will be shown below, it is necessary only that the initial photoelectron pulse duration be somewhat less than the transit time of the fastest electrons in the pulse.

In Figures 2a-2c the theory of the electron current transient shape is developed schematically. The figures are not drawn to scale, and the effects of diffusion, electron multiplication, and the finite ultra-violet light pulse, are shown only qualitatively.

Figure 2a represents an idealized case in which the initial pulse of photoelectrons is considered to be a thin slab, and in which only the effect of diffusion is illustrated. In the lower half of the
Figure 1. Diagram showing the electronics used to measure drift times.
figure the pulse of electrons is shown spreading out as it progresses across the tube from the cathode to the anode. (The areas under the curves a-d should be the same, although they are only approximately so in the drawings.) In the upper half of the figure the electron current rises linearly from A to a maximum value at B, determined by the number of electrons in the pulse and the drift velocity, and remains constant from B to C, at which time the first electrons reach the anode. The decay follows the curve from C to D according to the shape of the pulse at the time it reaches the anode. With no diffusion the decay would follow the dashed path CEF. The time of flight of the pulse is seen to be simply the half-width of the curve ABCD as is indicated by $t_d$.

In Figure 2b an initial photoelectron spacial distribution somewhat similar to that actually used in the experiment is assumed (see Figure 4). Again only the effect of diffusion is considered. The current is seen to rise from A to B, whereupon it remains constant until C is reached. With no diffusion the path followed would be that indicated by the dashed line CEF. However, diffusion causes a spreading out of the initial pulse a, as is illustrated by pulse b, and the actual curve falls from C to D. As in the previous case it is readily seen that the transit time corresponds to the half-width of the curve ABCD.
Figure 2. Schematic development of the theory of the electron current transient shape.
In Figure 2c we consider a third case. This time electron multiplication is added to the picture. As the electric field $E$ is increased, more and more of the initial photoelectrons cause the gas to become ionized, producing positive ions and electrons. Because of their relatively low velocities the positive ions' contribution to the current observed is very much smaller than that of the electrons and is not considered here. The effect of electron multiplication due to ionization by collision is to cause the electron current to rise from $B$ to $C$ as shown in Figure 2c rather than to remain constant as in the case presented in Figure 2b. In Figure 2c the initial spatial distribution of photoelectrons is assumed to be the same as in Figure 2b. Due to the electron multiplication, however, the area under the curves representing spatial distribution increases (pulse $b$, dashed line), while diffusion, in addition, causes a spreading out of the electron pulse as is shown by the solid curves for pulses $a$ and $b$. The electron current thus increases as electrons traverse the tube, rising from $B$ to $C$. At $C$ the current drops again, following the curve shown to $D$ as electrons are collected at the anode. The time $t_1$ shown in Figure 2d represents only approximately the drift time. The time $t_d$ will be a correct measure of the drift time provided the drift time is longer than the spread in time of the pulse of electrons. However, multiplication is not significant.
for drift time measurements at values of \( E/p_0 \) below about 10 volt\text{-}cm\(^{-1} \) Torr\(^{-1} \). For Hydrogen at \( E/p_0 = 15 \), \( \alpha/p_0 = 2.6 \times 10^{-4} \text{cm}^{-1} \) Torr\(^{-1} \) according to Rose (23, p. 273), where \( \alpha \) is the first Townsend ionization coefficient. * This corresponds to a one percent current rise due to electron multiplication for the 1.37 cm electrode separation used.

Further spreading of the observed transient shape is caused by the finite risetimes of the oscilloscope and amplifiers. As will be shown in Part III, these risetimes are very short and may be ignored. Photoionization in the gas and additional photoelectron production at the cathode resulting from decay of excited atoms also give rise to small effects which may be ignored as well at the values of \( E/p_0 \) considered here. The production of secondary electrons by positive ion bombardment of the cathode does not present itself as a problem either due to the fact that the ion drift times are an order of magnitude longer than those of the electrons. Furthermore, positive ion production is low for the values of \( E/p_0 \) used in the present experiment.

Figure 3 illustrates, without showing diffusion or electron multiplication, the effect of using an ultra-violet light pulse which is longer than the electron drift time. For simplicity a long pulse

\* See p. 45 for the method of normalizing \( p \) to \( p_0 \).
Figure 3. Diagram showing the effect of light pulses of long duration on the measured drift time.
ABCD is assumed, where AD is longer than $t_d$. The current is seen to rise from D to E, then to remain constant to F, and finally to fall to zero at G. The measured drift time (assumed to be the half-width of the time-current plot if the light pulse's length be ignored) is then $t_d + t'$ rather than the actual drift time $t_d$.

One should expect the measured drift time in a gas to be too long when the actual drift time is of the same order of magnitude as the length of the light pulse. Indeed, this seems to be borne out by this experiment, for it is at approximately 0.5 microseconds (the same order of magnitude as the light pulse length) that our observed hydrogen drift velocity data appear to depart slightly from those taken by Bradbury and Nielsen (1, p. 388) and, more recently, by Pack and Phelps (18, p. 798), in which an electric shutter technique was used. Further discussion of this point appears on p. 48 below.

Although our discussion has up to this point been concerned entirely with electron drift velocities, it is possible to use the same experimental method to measure ion drift velocities as well. In fact, drift velocity data were taken for ions in mixtures of hydrogen and deuterium. It was hoped that these measurements would yield definite information about the identity of the ions whose drift velocities were measured in their parent gases by Rose (22, p. 643-645) for deuterium and by Chanin (4, p. 526-528) for hydrogen. Although
good agreement with the drift velocities reported by Rose and Chanin was obtained for \(20 \leq \frac{E}{p} \leq 30\) volts\(\cdot\)cm\(^{-1}\) T\(\text{orr}^{-1}\) in the pure gases, only one drift velocity was observed in a given mixture of \(H_2\) and \(D_2\) or of \(H_2\), \(HD\), and \(D_2\). It was thought it would be possible to observe more than one ion at a time in the gas mixtures, e.g., \(H_3^+, H_2D^+, HD_2^+, \text{and } D_3^+\). However, no useful information leading to the identification of the ions involved was obtained.
III. DESCRIPTION OF THE EXPERIMENTAL PROCEDURE


The discharge tube which was used to make the present drift velocity measurements is shown schematically in Figure 1. It was fabricated at the Physics Department of the University of Washington and was kindly lent for this experiment by D. S. Burch, who describes it in detail (3, p. 13-17, 89-92). It consists of an oxide coated cathode illuminated by ultra-violet light from a spark light source. The light passes first through a quartz window located just beneath the anode and then through the anode, which is perforated by small holes. The anode is made of nickel plated copper, while the cathode base metal is a molybdenum disk, the edge of which is spun over a steel spider. Both electrodes are 40 mm in diameter. They are parallel to better than three percent.* The cathode is mounted on a barrel, which is threaded on its inside to go over the cathode lead-out. Nickel plated soft iron armatures are mounted opposite each other on the outside of the barrel. The separation between the anode

* This figure is given by Burch (3, p. 16). Recent measurements indicate the electrodes are parallel to better than one percent for a separation of 1.3 cm. However, the latter measurements had to be made with the cathetometer in a fixed position with respect to the tube, because there was only a small opening in the aquadag on the inside of the tube through which the electrodes could be observed.
and the cathode can thus be adjusted from the outside of the discharge tube by rotating the armature by means of a strong permanent magnet. The inside of the discharge tube around each electrode is painted with a band of aquadag approximately three-quarters of an inch wide. These bands are connected to each other and to a lead-out on the vacuum line by more aquadag and silver paint. In practice the aquadag is kept at about one-half the anode potential, although, according to Burch (3, p. 16), wide variations in the aquadag potential have no effect on the observed transient response of the tube. The entire discharge tube is surrounded by a copper box, which is grounded and serves to shield the tube from spurious electromagnetic radiation produced by the light source. The cathode follower discussed below is built into a small box, which rests on top of the tube shield to which it is connected electrically. The grid pin of the triode connected 6AK5 cathode follower is soldered directly to one end of a banana plug, while the other end of the plug fits inside the one-quarter inch Kovar tubing, which serves as the discharge tube cathode lead-out. The anode-cathode separation is measured by means of a cathetometer through a hole in the tube shield opposite the electrodes. The capacitance of the tube itself for the electrode separation used was measured with a Tektronix Type 130 L-C meter and found to be $\approx 6$ pf. The overall capacitance of the tube
including that due to the cathode follower is estimated to be less than 15 pf.

The cathode follower is mounted in a small copper box, the dimensions of which are about 2 1/2" x 2 1/2" x 1", and on which are mounted three SO-239 coaxial cable connectors used to connect it with the batteries which supply the heater and plate voltages and with the wide band amplifier. In order to reduce the input capacitance a tube socket was not used. Connections to the 6AK5 were made by soldering leads directly to the tube's pins. The 10K ohm variable resistor, R, was constructed from a carbon potentiometer in order to minimize the capacitance between the grid and ground. The resistance element was removed from the original potentiometer case and mounted on a lucite block. The sliding contact, as well, was mounted on a lucite rod which passes through the side of the amplifier housing. A numbered scale makes it possible to determine the resistance of R with the aid of a calibration curve. In this manner an approximate RC constant for the discharge tube can be found.

The signal coming from the cathode follower is amplified by a Tektronix Type 1121 amplifier, having a gain of one hundred and a passband stated by the manufacturer to be greater than 17 megacycles/sec. The stated rise time of the amplifier to 90 percent of
full signal is 21 nanoseconds.

The output of the wide band amplifier is connected directly to a Tektronix Type 533 oscilloscope, which is used with a Type L plug-in amplifier. The Type 533-Type L combination is said by the manufacturer to have a 15 megacycle/sec bandpass and a rise time of 23 nanoseconds. The oscilloscope triggering signal is obtained by means of a wire which is loosely coupled to the lead which connects the 7.5 KV transformer to the capacitor C across which the spark is produced. Since a signal delay of 0.2 microseconds is built into the oscilloscope, the trace is horizontal in the pictures shown in Figure 8 and does not begin to rise until 0.2 microseconds have elapsed. The sweep frequency of the oscilloscope was calibrated against a 2.5 megacycle/sec signal from an Army Type BC-221 frequency meter, which in turn had been compared with a 5 megacycle/sec signal from WWV, the time standard radio station at the U. S. Naval Observatory. For some of the electron drift velocity measurements a calibration signal was photographed in order to determine the drift velocity from the transient pictures without recourse to the oscilloscope calibration. (See Figure 8 for an example of these pictures.) The linearity of the oscilloscope was also checked by means of measurements made on photographs of the 2.5 megacycle/sec signal derived from the frequency meter and was found to be
better than 0.5 percent.

The potential difference across the discharge tube is furnished by a shielded battery supply, the voltage output of which is continuously variable up to approximately 1245 volts, or the battery supply in conjunction with a Fluke Model 409A regulated high voltage D.C. supply.

All voltage measurements were made with a Cubic Model V-45 digital voltmeter, which had been checked against a standard cell. The four digit voltmeter is stated by its manufacturer to have an accuracy of ± 1 digit.

The source of light used to release photoelectrons from the cathode of the discharge tube is a high intensity repetitive spark which is synchronized with the 60 cycle/sec A.C. line. Reference is again made to Figure 1. The capacitor C is charged through the resistor X by the high voltage transformer T₂. A spark is produced across the gap SU between the ring S and the adjustable pointed tungsten electrode U upon the production of air ions by a tickler spark between Y and S. The output voltage of the high voltage transformer T₂ is adjusted by the autotransformer so that a spark will not occur between S and U until a tickler spark of proper phase relationship to the voltage across C takes place. The tickler supply circuit is similar to one used by Hornbeck (15, p. 374)
at Bell Telephone Laboratories and was constructed by Burch. In practice there are a number of variables involved in producing a satisfactory spark. These include the width of the main gap between S and U, that of the tickler gap between Y and S, the voltage at which the transformer \( T_1 \) is set, the intensity of the tickler spark, and finally the phase relationship between the tickler spark and the high voltage from \( T_2 \). Because an exposure of one second's duration is used in photographing the transient waveform of the discharge, each photograph involves some sixty flashes of the spark. Hence, to avoid "noisy" pictures, it is necessary that the sparks be highly uniform. That is, each individual spark must take place between the tip of the electrode U and the same point on S near the tickler. In general, it is desirable that the flashes of light be as bright as possible to produce a copious supply of electrons at the cathode. To make them so one increases the gap between S and U and raises the output voltage of \( T_2 \). However, as the gap between S and U is lengthened, the spark has an increasing tendency to wander over the surface of S, producing erratic light flashes of varying intensity and duration. Normally, \( T_2 \) was set at about 4.6 KV. Above this voltage it was difficult to keep the spark stable. It is to be noted that for a bright spark of very short duration one wants a large value of capacitance for C and a very low inductance in C and in the gap
electrodes. For this reason the gap electrodes are mounted directly on the capacitor C.

The duration of the light flashes produced by the spark source was measured using a 5653 vacuum phototube and a Tektronix Type 519 oscilloscope, the rise time of which is 0.23 nanoseconds. The phototube anode potential used was approximately 1100 volts, while the oscilloscope was connected across a 100 ohm carbon series resistor. The capacitance between the anode and cathode base pins of the 5653 was measured with a Tektronix Type 130 L-C meter with the high voltage supply disconnected and found to be approximately 5 picofarads. Hence, the RC constant of the circuit is about $5 \times 10^{-10}$ seconds. The observed transient is shown in Figure 5. The rise time of the pulse is about $2.5 \times 10^{-8}$ seconds, while its half-width is about $2 \times 10^{-7}$ seconds. The total pulse length is about $4 \times 10^{-7}$ seconds. The vacuum photoelectric pulse produced in the experimental tube — another and probably better measure of the light pulse — was slightly longer than $2 \times 10^{-7}$ seconds, with a half-width of about $1 \times 10^{-7}$ seconds for $R = 6$ ohms, where $R$ is shown in Figure 1. Figure 4 shows the observed pulse shape. It is not surprising that Figures 4 and 5 are not identical. In the first place the 5653 phototube has an S-4 response with a peak sensitivity at about 4000 Å and a short wavelength cutoff at 3000 Å, whereas the corresponding cutoff due to the quartz window of the experimental tube is
Figure 4. Vacuum photopulse obtained using the experimental tube.

Figure 5. Transient obtained by observing the light from the spark with a type 5653 phototube.
below 2400 Å. In addition the drift distances are not the same. For the 5653 it is about 0.8 cm, while for the experimental tube it is about 1.4 cm. Furthermore, the response of the photocathode of the experimental tube as a function of wavelength is not known.

If the input resistor to the cathode follower (R in Figure 1) is assumed to have its maximum value of 10 Kohms and the capacitance of the discharge tube is taken as 20 pf, the RC constant of the discharge tube is then about $2 \times 10^{-7}$ seconds. That is, it is approximately of the same duration as the light flash. Thus, for ion mobility studies in which $R$ must be large in order that the observed signal be of reasonable size, there is no need for a spark of shorter duration. The limiting factor is the RC constant of the discharge tube. In the case of electron drift velocity measurements, on the other hand, the rather long duration of the spark apparently limits us, in studying hydrogen, to values of $E/p_o$ less than about 5 volts-cm$^{-1}$-Torr$^{-1}$ for our drift distance of about 1.4 cm.

Shielding the amplifiers and external circuitry from unwanted radiation produced by the spark source was a considerable problem. The A.C. line connection to the autotransformer was shielded (see Figure 1), as were the connections leading into and away from the high voltage transformer $T_2$, while the spark gap and tickler supply were located within a tightly sealed copper box. Even
with these precautions it was necessary to be very careful in the
physical positioning of the various connecting coaxial cables to pre-
vent ringing induced by the spark.

Part 2. Vacuum system and gas handling.

The gas samples used in the experiment are introduced to the
discharge tube by means of a high vacuum system, which is illus-
trated schematically in Figure 6. The discharge tube is mounted
vertically on top of the vacuum table above a one inch hole in the
transite table top, the hole serving as an aperture for the light from
the spark source beneath. The high vacuum bakeout valves 1-3
(Granville-Phillips Type C) are the only components other than the
manifold M, the discharge vessel, and the connecting tubing mounted
on top of the table. A Varian 8 liter/sec Vacion pump mounted be-
neath the table is connected between bakeout valves 1 and 2. Bake-
out valve 2 is connected through liquid nitrogen trap B and high vac-
uum stopcock 4 to the roughing pump, which is a Cenco Megavac.
The pressure of the roughing pump line is measured with a thermo-
couple gauge connected to the line through high vacuum stopcock 5.
In addition to being used to pump the system down to a pressure at
which the Vacion pump will operate efficiently, the roughing pump
is also used to evacuate one side of the manometer during gas
Figure 6. Vacuum and gas handling system.
pressure measurements. For this purpose the roughing pump is connected to the manometer through high vacuum stopcock 6. A liquid nitrogen trap A is used to isolate the high vacuum side of the system, comprising the manifold M, the discharge tube, and the tubulation leading to the break-off seal on the hydrogen flask C, from the grease (Apiezon N) of stopcocks 9-12 and from the Octoil with which the manometer is filled. (A better solution to the problem of avoiding contaminating the high vacuum part of the system with stopcock grease, manometer oil, or gases released therefrom, would be to separate the manometer from the high vacuum side by means of a bakeable stainless steel bellows, which could be used as a null-reading pressure measuring device. This would avoid having to employ liquid nitrogen trap A. Such a device was constructed, but, because it did not in fact perform satisfactorily, it was not used.)

The manometer, which is mounted on the side of the vacuum table is approximately 95 centimeters in length overall, making it possible to measure with it gas pressures up to somewhat more than 80 cm of Octoil. At \(20^\circ C\) Octoil has a density of 0.9835 gm-cm\(^{-3}\). Hence, at this temperature, 80 cm of Octoil corresponds to about 58 Torr. To ensure that the manometer oil be thoroughly outgassed initially, it was distilled from a small auxiliary flask into the manometer at a
few microns of mercury pressure. When this operation was completed the flask was sealed off from the system, leaving the stub F on the manometer. Additional outgassing was sometimes accomplished by flaming the manometer tubing and then moving a small steel ball up and down in the warmed manometer oil by means of an external magnet.

The density of Octoil used in all pressure measurements was taken from a plot of density-temperature data furnished by Consolidated Vacuum Corporation. The temperature of the oil was measured with a mercury thermometer in contact with the manometer.

One liter flasks of Airco reagent grade hydrogen were attached to the line leading through the table top to bakeout valve 3. The connecting tubing is vertical and has a short arm S attached to it, in which is placed a glass encapsuled iron slug W before sealing the flask C to the system. After baking out the system, valve 3 is closed and the iron slug is removed from the arm from the outside by means of a strong permanent magnet and is then dropped on the break-off seal of the flask.

A palladium leak E, shown schematically in Figure 6, was attached to the system through high vacuum stopcock 11. (For a discussion of palladium leaks and further references see Reference 9, p. 519, 574, 577, 578.) A one liter gas storage flask D is
connected through high vacuum stopcock 12 to the line between the leak and stopcock 11. Flask D was necessary due to the slow rate of diffusion through the leak, which was the result of using too small a palladium thimble in the construction of the leak. The leak is operated by filling the envelope which surrounds the palladium thimble with either tank hydrogen or tank deuterium to a pressure of about 0.8 atmosphere as measured on gauge G, after first having evacuated the envelope and the hoses connecting the point H in Figure 6 to the tank of gas. Stopcock 13 is then closed, and the current through the tungsten filament surrounding the palladium thimble is adjusted by means of the autotransformer J connected to the primary of the low voltage transformer I until the glow of the filament is barely perceptible in a darkened room. If stopcock 11 is left open with the Vacion pump on, one finds no rise in pressure as determined from the Vacion pump current if the envelope of the leak is filled with air, oxygen, nitrogen, or helium with the leak heater on. However, as soon as hydrogen or deuterium is introduced to the leak's envelope — even with the heater off — the pressure rises immediately to a value above $10^{-4}$ Torr.

A small flask, L, equipped with a stopcock and a male ground glass joint, was used to carry gas samples to a Consolidated Engineering Corporation Model 21-401 mass spectrometer for
analysis. The flask was attached to the system at the female ground glass joint, K, and was evacuated, prior to the collection of a gas sample, by means of the Vacion pump to which it was connected through stopcocks 7 and 8 and bakeout valve 2. During this evacuation procedure liquid nitrogen trap B was kept filled, and stopcocks 10 and 6 were closed with 9 open.

As part of the ion mobility study mentioned above on page 15 HD was produced in mixtures of D₂ and H₂ by running a glow discharge in the experimental tube. The resulting HD concentration was then determined by means of the mass spectrograph.

The high vacuum part of the system was subjected to prolonged baking at temperatures in excess of 300°C. To accomplish this a portable oven was lowered over the system components on the top of the vacuum table, with the exception of bakeout valve 2, which remained closed during the bakeout process and could not withstand the high oven temperature. It was outgassed with the aid of a Veeco heat gun. The tubulation connecting flask C, the Vacion pump, and trap A to the manifold M, as well as trap A itself, were wrapped with heating tape, the temperature of which was measured by means of thermocouples buried beneath the tapes, and was adjusted by means of autotransformers. Several thermocouples were also used inside the oven to measure the temperature above
The procedure followed during bakeouts is outlined below.

After roughing the system through liquid nitrogen trap B with all bakeout valves open and with stopcocks 8, 10, and 11 closed, bakeout valve 2 is shut. The Vacion pump is then turned on, and the system is pumped down to a pressure of approximately \(2 \times 10^{-7}\) Torr as determined from the Vacion pump current using the calibration furnished by the pump manufacturer. The pump current and, hence, the pressure, is monitored continuously during the bake-out process by means of a Nesco Model JY-120 recording potentiometer. The temperature of the heating tapes and of the oven is increased slowly, so that the pressure of the system never exceeds \(5 \times 10^{-5}\) Torr. The average pressure during the first stages of baking is normally kept at about \(5 \times 10^{-6}\) Torr. During a typical bakeout the pressure reached \(10^{-7}\) Torr at slightly above 300°C after 72 hours of baking. After shutting off the oven and heating tapes the pressure dropped to below \(10^{-8}\) Torr. The gas storage flask D (see Figure 6) was outgassed by flaming it until a rise in pressure was no longer observed upon reheating it after having let it cool. In a similar manner the tubulation connecting trap A to stopcocks 10 and 11 was also outgassed. During bakeouts the heater of the palladium leak was kept above its normal operating temperature. In the last stage of the
bakeout process, before the oven or other heating tapes are shut off, the heating tape is removed from trap A, which is then immersed in liquid nitrogen. Subsequent to this the other heating elements are turned off.

In order to determine the amount of contamination of the gas under study during a data run due to outgassing of the tube walls, the following check was made. Prior to each data run, but following the bakeout described above, the evacuated discharge tube was sealed off from the Vacion pump by closing bakeout valve 1. After periods as great as eleven hours the pressure as determined from the Vacion pump current upon re-opening bakeout valve 1 remained below $2 \times 10^{-8}$ Torr. Using the same technique, the extent of outgassing of the oil manometer was checked. This was done by first evacuating the left hand side of the manometer, as shown in Figure 6, through stopcock 10 with stopcock 9 closed. Stopcock 10 was then closed for a period longer than that necessary to take a gas pressure reading using the manometer during a data run. The pressure of the system as determined from the Vacion current upon re-opening stopcock 10 remained below $3.6 \times 10^{-8}$ Torr for eighteen minute intervals. A similar check of the palladium leak and the gas storage vessel D with stopcock 12 open indicated a pressure rise of $4 \times 10^{-8}$ Torr per hour. Thus, during the twenty-four hour periods
necessary to obtain usable quantities of hydrogen and deuterium through the leak, the pressure rose to approximately $10^{-6}$ Torr, resulting, however, in an impurity of less than 1 ppm in the gas studied.

Part of the hydrogen data was taken using flasks of Airco reagent grade hydrogen, represented by C in Figure 6. A typical mass spectrographic analysis of this gas is given by the Matheson Co. as 0.0005% O₂, 0.000% N₂, 0.000% CO₂, and 0.0005% H₂O, for a total impurity level of 10 ppm. The other part of the hydrogen data was taken using NCG tank hydrogen which had been passed through the palladium leak according to the procedure outlined above. There is no significant difference between the data taken using these two methods, although it is believed that the hydrogen passed through the palladium leak is the purer.

The deuterium used was obtained in 1.4 liter cylinders at 250 psi from the General Dynamics Corporation, which guarantees its purity as 99.5 atom % D. A typical gas analysis described by the manufacturer is the following: 99.66 ± 0.05 mol % D₂, 0.34 ± 0.05 mol % HD, less than 0.06 mol % D₂O-H₂O, less than 0.2 mol % H₂.

The deuterium was introduced into the system in one of two different ways. In the first method the tank deuterium was passed
through a liquid nitrogen trap into a one liter pyrex flask with a
break-off seal at its other end, as is illustrated in the drawing of
flask C in Figure 6. The flask and system up to the deuterium
tank valve were evacuated to below $10^{-7}$ Torr before filling the flask
to about 0.5 atmosphere. The deuterium tank was connected to a
brass bellows or "Sylphon", which in turn was attached to a metal-
to-glass seal. This flask of deuterium was attached to stopcock 11
(see Figure 6) before the palladium leak and stopcock 12 were added
to the main vacuum and gas handling system. During the bakeout
procedure following the attachment of this flask, the tubulation con-
necting it through stopcock 11 to liquid nitrogen trap A was out-
gassed by flaming. It is to be noted that the gas introduced in this
manner must pass through liquid nitrogen trap A.

The second method of introducing deuterium employed the
palladium leak. The rate of diffusion, $q$, of hydrogen and of deu-
terium through palladium is proportional to $P^{1/2}$ when $P$, the pres-
sure difference across the metal, is greater than about one atmos-
phere. (9, p. 574-577) Under these conditions, the solubility, $s$,
of deuterium or hydrogen in palladium is also proportional to $P^{1/2}$.
At $300^\circ$ C, which is the estimated temperature of the leak during
operation, $s_D/s_H = 0.67$. (9, p. 541) Hence, $q_D/q_H \approx 0.67$. It
is thus apparent that deuterium passes through the palladium leak
less rapidly than hydrogen, tending with time to increase the \(H_2\) impurity concentration of the gas. If one assumes that the only impurities in the tank deuterium are 0.34\% HD and 0.2\% \(H_2\), and that the operating temperature of the palladium thimble is 300\(^\circ\)C, the hydrogen impurity increases from one part per 270 to one part per 180 as a result of passing the deuterium through the leak. At temperatures above 300\(^\circ\)C, \(s_D/s_H\) becomes more favorable. It is, for example, 0.82 at 600\(^\circ\)C, 0.87 at 800\(^\circ\)C, and 0.91 at 1000\(^\circ\)C. (7, p. 519). As in the case of hydrogen discussed above, there is no significant difference between the data obtained using gas prepared by either of the two methods.

In Figure 11 electron drift velocity data are presented for an 80.3\% \(D_2\)-19.7\% \(H_2\) mixture. It is seen that with this percentage impurity of \(H_2\) at \(E/p_0 = 0.7\) the increase in drift velocity is only 4\% greater than in the case of "pure" deuterium. On the basis of this result it is thought that a hydrogen impurity as high as one part per 180 in the deuterium, or 0.56\%, (which is an upper bound) would not be detectable using the present experimental technique.

Part 3. Data taking.

The gas pressure was measured at the start of each data run using the Octoil manometer. (Octoil has a vapor pressure of about
2 x 10^{-7} \text{Torr} at 25^\circ \text{C}, and at -10^\circ \text{C} it is well below 10^{-9} \text{Torr}.)

Because the density of Octoil is temperature dependent, the oil manometer readings were converted to Torr using temperature-density data obtained from the Consolidated Vacuum Corporation. The oil temperature was taken with a mercury thermometer in contact with the manometer. The manometer was allowed to be in contact with the gas being measured for about fifteen minutes to allow it to reach equilibrium. This length of time was needed because of the relatively high viscosity of the oil at room temperature; it takes about this long for the oil to run down the manometer tubing after the introduction of gas. The height of the oil column was measured using a cathetometer for heights less than about 47 \text{cm} of oil. For heights greater than this a meter stick read with the aid of the cathetometer was used. This latter method of measurement had to be adopted because the cathetometer scale did not extend below a distance of about 17 \text{cm} above the floor. The pressure measurements are thought to be accurate to better than \pm 0.5\%.

The temperature of the discharge tube was measured to approximately \pm 0.1 \degree \text{C} at intervals during data runs with a mercury thermometer in contact with the tube's copper shielding.

The anode-cathode separation was measured on the axis of the experimental tube with a cathetometer to \pm 0.01 \text{cm}. The two
electrodes were out of parallel by not more than one percent for the separation of 1.37 cm used in this experiment. (See the note on p. 17)

The oscilloscope and amplifiers were allowed to warm up for a period of at least one hour prior to the taking of data to ensure reasonable stability over the period during which data were taken.

The procedure used to obtain the experimental data was essentially the following. After determining the gas pressure and oil temperature as indicated above and closing stopcock 10 (see Figure 6) to isolate the manometer from the discharge tube, the spark light source was adjusted until its performance was satisfactory. The voltage across the tube was then adjusted to give the desired electric field. Following this, the voltage was measured on the digital voltmeter just prior to taking a one second exposure at f. 2.8 of the transient displayed on the oscilloscope, using fast Polaroid film (ASA 3000) in a Polaroid Land camera. From three to five different transients were recorded on a given 3.8" x 2.9" film frame (see Figure 8). Immediately following the taking of a picture were noted: (1) the value of R, the cathode follower grid resistor shown in Figure 1; (2) the amplification used; and (3) the oscilloscope sweep rate. In some runs one of the exposures on a given film frame was of a display of a 2.5 megacycle signal from a BC-221 frequency
meter (see for example Figure 8).

With the above recorded information at hand one then normalizes the pressure, $P_t$, which was measured at temperature $T$, to the pressure at some standard temperature, for example $p_o$, where $p_o = (273/T) p_T$ Torr. Here $T$ must be in degrees Kelvin. The electric field, $E$, is then calculated, where $E = V/d$, in which $V$ is the tube potential in volts and $d$ is the anode-cathode separation in centimeters. Following this is found the quotient $E/p_o$, of which the drift velocity, $v_d$, is a function. The drift velocity is the quotient of the drift distance, $d$, i.e. the separation of the tube electrodes expressed in centimeters, by the drift time, $t_d$, in seconds, determined from the transient shapes in the manner outlined below:

$$v_d = \frac{d}{t_d} \text{ cm-sec}^{-1}.$$

Reference is made to Figure 7 in which is illustrated schematically the shape of a typical transient. The oscilloscope is triggered at A by the spark light source. However, because the oscilloscope has a built-in 0.2 microseconds signal delay, the trace does not rise until the point B is reached, the distance AB corresponding to 0.2 microseconds. The widths AA', BB', CC', etc., in the diagram represent the observed noise level. The drift time, taken to be the half-width GH, is found directly from the film by means of a low power travelling microscope, which is calibrated in
Figure 7. Schematic diagram of a typical electron transient.
thousandths of centimeters along the axis with which the time base on the photographs is aligned and in thousandths of inches in the direction perpendicular to this. Thus, the distance JI (from the center of the base line noise to the center of the noise at the peak of the curve) is measured to the nearest thousandth of an inch. From this one-half JI is obtained, and the point K is located, where JK = KI, establishing the line GH. Measurement of the distance GH follows, readings at G and H being taken at the center of the noise. The measured distances GH vary between 1 and 4 cm and are reproducible to better than ±0.015 cm. It is thought that the experimental uncertainty in the drift times is less than 1.5%.

While the drift velocities reported were all taken with a drift distance of 1.37 cm, earlier data taken with a drift distance of about 1.9 cm are in excellent agreement with the former, indicating that the measured drift velocities are independent of d.

By means of Equation (14), p. 7, it is possible to determine approximately the distance \( x_g \) needed for an electron to reach a fraction \( g = w/w_t \) of its terminal energy, \( w_t \). If one assumes \( g = 0.99 \) for electrons in hydrogen and uses the mean free path data of Townsend and Bailey quoted by Loeb in Reference 17, p. 325, taking \( E/p = 0.25 \text{ volts-cm}^{-1}\text{-Torr}^{-1} \) and \( p = 29 \text{ Torr} \), this being the worst case for the present experiment for \( E/p \geq 0.25 \), it is found that
\[ x_g = 0.087 \text{ cm}, \text{ indicating that the electrons have reached 99 percent of their terminal energy within 0.087 cm from the cathode. Because } \]
\[ g = \frac{w}{w_t} = \left(\frac{u}{u_t}\right)^2, \text{ we find that } \frac{u}{u_t} = g^2 = (0.99)^2 = 0.995; \text{ that is, } \]
the electrons reach approximately 99.5 percent of their terminal velocity, \( u_t \), within 0.087 cm from the cathode. The result of the finite distance necessary for the electrons to reach their terminal velocity is thus to alter slightly the shape of the front edge of the observed current pulse. We ignore this effect, however, as being too small to change significantly the measured electron drift times. This is borne out as indicated in the preceding paragraph.

In Figure 8 are presented typical photographs of the electron current transients observed. The left-hand column of pictures is for hydrogen, while the right-hand column is for deuterium. The noise level for the hydrogen pictures appears to be higher than for the deuterium pictures because the amplifier gain used was higher. If the gain had been kept constant, the height of the individual curves would have increased with increasing \( E/p_o \), the increase corresponding to the diminishing effect of back diffusion of electrons to the cathode. In practice, however, the value of the grid resistor of the cathode follower (R in Figure 1) was decreased as the observed
Fig. 8. Typical transient photographs for 1.37 cm drift distance.

H₂ - 0.5 μsec/cm sweep,
T = 24.5°C, P₀ = 28.7 Torr.

D₂ - 0.2 μsec/cm sweep,
T = 24°C, P₀ = 41.7 Torr.
electron current increased, thus reducing the RC constant of the experimental tube. As a result of this the electron transients shown in Figure 8 appear to be of approximately constant amplitude.
IV. DISCUSSION OF RESULTS

In Figures 9-13 our experimental results are presented. The overall experimental uncertainty in the measurement of the quantity $E/p_0$ is estimated to be about ±1.5%, while that of the drift velocity, $v_d$, is estimated to be about ±2.5%. In hydrogen at $E/p_0 \approx 1$ this leads to an overall uncertainty in $v_d$ of ±3.5%. That is, if $E/p_0$ is specified, $v_d$ is thought to be known to about ±3.5%. From the graphs it is apparent that the scattering of the data lies within approximately this range.

It is to be noted that the range of available $E/p_0$ was limited by two factors. First, at low $E/p_0$ the signal-to-noise ratio becomes intolerably low. For this reason we do not give data for $E/p_0$ below 0.1 volt-cm$^{-1}$Torr$^{-1}$. Second, at high $E/p_0$ the drift time, $t_d$, becomes the same order of magnitude as the length of the light pulse used. Thus, our results for hydrogen are somewhat uncertain for $E/p_0$ greater than about 5 volt-cm$^{-1}$Torr$^{-1}$. We present data for $E/p_0$ up to about 20 volt-cm$^{-1}$Torr$^{-1}$, however, for the purpose of comparing them with those of other workers.

In order to facilitate the comparison of data taken by various experimenters, all values of $E/p$ have been reduced to $E/p_0$, where $p_0 = (273/T)p_t$, or $E/p_0 = (T/273)E/p_t$, in which $T$ is the
temperature in degrees Kelvin corresponding to the centigrade temperature, t, at which the pressure $p_t$ was taken. Thus, if $E/p_{20}$ has been given in the literature, we have plotted $E/p_o = (293/273) E/p_{20}$.

Figure 9 gives our data for hydrogen. For comparison are plotted: the solid curve, which represents a best fit to the data of Bradbury and Nielsen, who used an electric shutter technique (1, p. 388-395); the recent data of Pack and Phelps (19, p. 11; first reported in Reference 18, p. 798-806) obtained using an improved electric shutter method, and which, incidentally, extend to a much lower range of $E/p_o$ than is indicated here; the published points representing a best fit to the pioneering work of Townsend and Bailey (24, p. 873-891), obtained using the so-called Townsend magnetic deflection method, and included because of their historical interest; the data of Frommhold (10, p. 554-567) obtained using a pulse technique somewhat similar to that of the present experiment in which a burst of electrons is caused to be emitted from the cathode by a very short flash of light from a spark discharge; and, finally, the data of Hall (12, p. 334-341) obtained by means of a refinement of Bailey's magnetic deflection method, which demands the assumption of an energy distribution function for the electrons.

Our results are seen to be in very close agreement with
Figure 9. Electron drift velocity as a function of $E/p_0$ in $H_2$. 

- This experiment
- Pack and Phelps (1960)
- Frommhold (1960)
- Hall (1955)
- Bradbury and Nielson (1935)
- Townsend and Bailey
those of Pack, Voshall and Phelps up to $E/p_0$ of about 3 volt-cm$^{-1}$ Torr$^{-1}$. Above this value our results fall slightly below those of Bradbury and Nielsen and somewhat more below those of Pack, Voshall and Phelps. No reason for this is evident unless it be that our measured drift times are long as a result of a spark which is too long. (See the discussion above beginning on p. 15.) Some, if not all, of the discrepancy between our data and those of Bradbury and Nielsen and of Pack and Phelps is due undoubtedly to experimental uncertainty in our data as well as in those of the other workers. It is observed also that the present data are not inconsistent with the data of Frommhold (10, p. 554-567), which extend from $E/p_0 = 20.1$ to $E/p_0 = 34.3$ volt-cm$^{-1}$ Torr$^{-1}$. The early (1921) data of Townsend and Bailey (24, p. 873-891) are seen to be some 20 percent higher than those of Bradbury and Nielsen, of Pack, Voshall and Phelps, or of the present experiment, for $0.26 < E/p_0 < 1$ volt-cm$^{-1}$ Torr$^{-1}$, at which point their data approach, with increasing $E/p_0$, the more recent work. The points given by Hall (12, p. 334-341) are consistently lower than those of any of the other workers, the two lowest points (between $E/p_0 = 0.2$ and $E/p_0 = 0.6$ volt-cm$^{-1}$ Torr$^{-1}$) being some ten percent low. It is to be remembered that Hall's results are dependent on the particular electron energy distribution function chosen — in this case that of Druyvesteyn (7,
p. 61-70) — and that at best such functions are only very approximate. For this reason it is not surprising to find her results deviating from the more direct experimental measurements. The three points due to Bailey quoted by Healey and Reed (13, p. 36) have not been plotted. They lie slightly above the data of Townsend and Bailey.

Our experimental data for deuterium are plotted in Figure 10. There is seen to be excellent agreement with the work of Pack, Voshall and Phelps (19, p. 14; 20, p. 2084-2089), while the data of Hall (11, p. 468-473) are significantly lower. On this basis it is to be concluded that the Druyvesteyn distribution is not — as is to be expected — the correct electron energy distribution function; it is merely close to the actual one.

Figures 11-13 represent data taken in mixtures of hydrogen and deuterium. These data were taken to investigate the effect of possible hydrogen contamination on our measured electron drift velocities in deuterium (see comments on p. 36 above) and are presented here only because electron drift velocities in H₂-D₂ mixtures have not been reported previously.
Figure 10. Electron drift velocity as a function of $E/p_0$ in Deuterium.
Figure 11. Electron drift velocities in H₂-D₂ mixtures as a function of E/p₀.
Figure 12. Electron drift velocity as a function of $E/p_0$ in a mixture containing 51.3% $H_2$ and 48.7% $D_2$. 
Figure 13. Electron drift velocity as a function of $E/p_o$ in a mixture containing 19.7\% $H_2$ and 80.3\% $D_2$. 

Drift Velocity ($cm\cdot sec^{-1} \cdot 10^{-5}$) vs. $E/p_o$ (volts-\(cm^{-1}\)-mm Hg\(^{-1}\))
V. CONCLUSION

Hornbeck's pulse technique (15, p. 374-379) has been applied for the first time to the measurement of electron drift velocities in hydrogen and deuterium and in mixtures of these two gases. Good agreement with the data of Bradbury and Nielsen (1, p. 388-393) and of Pack and Phelps (18, p. 798-806) is obtained for the case of pure hydrogen, and the agreement with the data of Pack, Voshall and Phelps (20, p. 2084-2089) is excellent for pure deuterium. For both gases the results of the present experiment lie significantly above those of Hall (11, p. 468-473; 12, p. 334-341) in which a Druyvesteyn distribution is assumed for the electron energy.


