TABLE II. Values of q_1/q_0 at various energies.

	3.8 ev	5.7 ev	7.1 ev	9.4 ev
Present results, ±20%	···	0.14	0.25	0.35
BDJS[a] with adiabatic polarization potential	0.4	0.5	0.6	0.7
John	0.09	0.19	0.23	0.28
McEachran and Frazer	0.09	0.19	0.23	0.28
Geltman	0.19	0.25	0.31	0.35

[a] See reference 4.

efficients A, B, and C could be determined. Remembering that the lth partial cross section is given by

$$q_l=\frac{4\pi}{k^2}(2l+1)\sin^2\eta_l,$$

the ratio q_1/q_0 could be obtained. This was done for the three energies 9.4 ev, 7.1 ev, and 5.7 ev, and the values are compared with several theoretical estimates in Table II.

Although the present experimental results can be explained in terms of s- and p-wave scattering only, we cannot rule out the possibility that there is an appreciable d-wave contribution. Indeed, Temkin and Lamkin,[11] using the method of polarized orbitals, have recently determined values of the d-wave shifts which, although far too small to support the results of BMH, are much larger than those given by either the exchange or the Born approximation. However, the manner in which the partial waves combine in this calculation gives resulting cross-section values which are also in fair agreement with the ones obtained in the present experiment.

In conclusion, we may say that the results do not show the strong forward peaking which would be required to substantiate the BMH results, whereas they are consistent with theory in that there are no unexpectedly large contributions from higher partial scattering cross sections. Unfortunately, the experimental uncertainties do not permit very precise comparisons with theory, so that it is not yet possible to resolve the small differences which result from different theoretical approaches.

We are indebted to a large number of theoretical physicists with whom we have discussed this problem, particularly our colleagues E. Gerjuoy and N. A. Krall, as well as A. Temkin, S. Geltman, and K. Smith.

[11] A.Temkin and J. C. Lamkin, preceding paper [Phys. Rev. **121**, 788 (1960)].

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Drift Velocities of Slow Electrons in Helium, Neon, Argon, Hydrogen, and Nitrogen*

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The drift velocities of electrons in helium, neon, argon, hydrogen, and nitrogen have been measured for E/p values between 10^{-4} and 10 volt/cm-mm Hg at temperatures between 77°K and 373°K. The data were obtained from measurements of electron transit time in an improved version of the double-shutter tube developed by Bradbury and Nielsen. By applying sufficiently small voltage pulses to the control grids, it was possible to eliminate end effects present in previous experiments. Values of the momentum transfer cross sections for electrons with energies between about 0.003 and 0.05 ev are obtained which are consistent with the measured drift velocities for thermal electrons in helium, argon, hydrogen, and nitrogen. The derived momentum transfer cross section for electrons in helium is found to be independent of electron energy and equal to 5.3×10^{-16} cm². The momentum transfer cross sections for argon, hydrogen, and nitrogen vary with electron energy.

I. INTRODUCTION

THIS paper reports measurements of drift velocities of electrons in helium, neon, argon, hydrogen, and nitrogen for low E/p values using an improved technique. The immediate purpose of this study was to obtain information about elastic collision cross sections from the measurement of electron drift velocities at very low E/p. The data were obtained with the drift tube which is an improved version of the one developed by Bradbury and Nielsen.[1] In a previous report[2] results were presented for helium in which certain end corrections appeared to be necessary at very low E/p. In Sec. II in this paper a technique is described in which end effects appear to be eliminated and greater accuracy is obtained. Measurements of electron drift velocities in argon, neon, helium, hydro-

* This work was supported by the Advanced Research Projects Agency, the Office of Naval Research, and the Air Research and Development Command.

[1] N. E. Bradbury and R. A. Nielsen, Phys. Rev. **49**, 388 (1936).
[2] A. V. Phelps, J. L. Pack, and L. S. Frost, Phys. Rev. **117**, 470 (1960).

gen, and nitrogen in the E/p range from 10^{-4} volt/cm-mm Hg to 10 volt/cm-mm Hg at gas temperatures from 77°K to 373°K are reported in Sec. IV. In Sec. V the data obtained at very low E/p in argon, helium, hydrogen, and nitrogen are used to obtain elastic scattering cross sections which are consistent with the measured drift velocities.

II. METHOD

The measurements of electron drift velocity were made using the electrode structure shown schematically in Fig. 1 and described previously.[2] Photoelectrons liberated from the cathode by ultraviolet light move downward under the action of a uniform electric field maintained by guard rings. The flow of current to the collector and electrometer can be reduced by the application of voltage pulses to alternate wires of the grids.[3] In the previous experiments a steady light source was used so that the first shutter was used to inject a pulse of electrons into the drift space. A second shutter was used to measure the transit time of the electrons from the first shutter to the second shutter. In an effort to correct for end effects, drift velocities were measured for two different drift distances and the difference in the measured transit times was used to calculate the drift velocity. This was accomplished by disassembling the tube, changing the spacing between the grids, and repeating all measurements.

In the present experiments the need for a grid to provide a time varying electron current is eliminated by the use of a pulsed light source. Either of the two grids can then be used to determine the time required for electrons to travel from the cathode to the grid. The difference in transit times gives the time required to travel between grids and should be independent of end effects occurring at the cathode and effects occurring equally at both grids. This type of operation is shown schematically in Fig. 1. Light from the pulsed light source produces a photocurrent leaving the cathode having the waveform marked I. The currents arriving at grid number 1 and grid number 2 are I_1 and I_2. Two limiting modes of operation of the grids have been used during the course of the present work. We will discuss first the "conventional" mode of grid operation which is essentially the same as that used by Bradbury and Nielsen.[1] Then we will consider the "zero bias" or "rejection" mode of grid operation.

Conventional Grid Operation

Conventional operation of the grids is as follows: A potential is applied between the two halves of grid number 1 such that electrons are collected. This bias

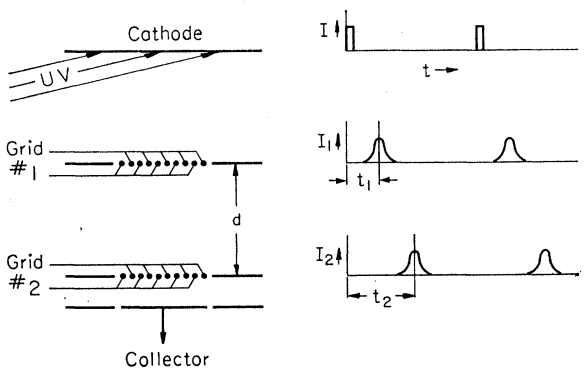

FIG. 1. Simplified schematic of drift velocity tube showing the conventional pulsed mode of operation. The widths of the pulses shown are not to scale.

is usually adjusted to reduce the transmitted electron current to about 5% of the value with zero bias. No voltages are applied between the two halves of grid number 2, which is passive during this measurement. In order to open grid number 1, a rectangular voltage pulse is applied symmetrically to each half of the grid so as to reduce the field between alternate grid wires to zero, i.e., to maximize the transmitted electron current when the delay is set at t_1. By varying the time delay between pulse applied to grid number 1 and the light pulse, a collector current versus time plot can be obtained which is similar to I_1. In like manner, by making grid number 1 passive and number 2 active, a collector current versus time plot can be obtained which is similar to I_2. If t_1 and t_2 are the locations of the peaks of these waveforms, and the symmetry of the waveform is not badly distorted by diffusion effects,[4] the drift velocity is given by $d/(t_2-t_1)$, where d is the distance between grid number 1 and grid number 2.

The lower curves of Fig. 2 show a set of current versus time plots obtained in hydrogen for an E/p of 0.02 volt/cm-mm Hg, $p=200$ mm Hg, and $T=300$°K. Here E is the electric field, p is the gas pressure, and T is the gas temperature. The peak value of I_2 is smaller than that of I_1 because of spreading of the electrons due to diffusion. The areas under the curves are the same, however, indicating that the effects of the two grids on the electron pulse are the same. Previously,[2] it was found that the diffusion coefficients calculated from the widths of the current peaks varied with experimental conditions in an unexplained manner about the expected values. This was not investigated further in the present work. Under most experimental

[3] For a summary of drift velocity measurements and grid designs see L. B. Loeb, *Basic Processes of Gaseous Electronics* (University of California Press, Berkeley, California, 1955), Chaps. I and III.

[4] R. A. Duncan, Australian J. Phys. **10**, 54 (1957). This paper discusses the correction to be applied to the drift time when a variable frequency control voltage is applied to the grid. Since the frequency is fixed in our experiments, the correction is smaller and is equal to $\sim 0.3(\Delta\tau/\tau)^2$, where $\Delta\tau$ is the width of current pulse at half maximum due to diffusion and τ is the time of maximum current. It can be shown that the correction to $(t_2-t_1)/d$ is proportional to $(\Delta\tau/\tau)^4$ and is negligible for our experimental conditions.

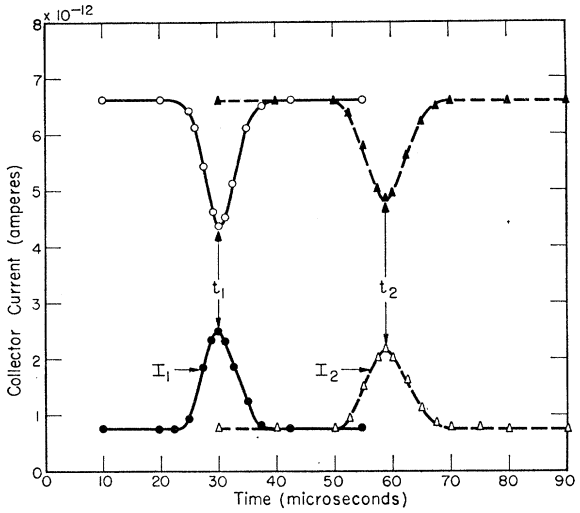

FIG. 2. Collector current vs time delay between the gate applied to either grid and the light pulse for $E/p=0.02$ volt/cm-mm Hg and a hydrogen pressure of 200 mm Hg. The grids were located at 2.54 and 5.08 cm from the cathode. The grid bias voltage and total pulse amplitude were 2 volts. The light pulse was 1.6 μsec long and the gate applied to the grids was 1.8 μsec long. The repetition rate was 7000 cps. The lower curves are for the grids operated in a biased fashion such that the transmission of grids increases during the application of gate. The upper curves are obtained with zero grid bias so that the transmission of the grids is decreased only during the application of the gate.

conditions the width of the voltage pulse applied to the grid was comparable with the width expected due to diffusion.

The value of bias required to reduce transmission of either grid to 5% depends upon pressure, E/p, and gas being studied. For helium, hydrogen, and nitrogen, the bias required is less than 40% of the potential difference between the two grids for moderate and large values of E/p. Under these conditions the ratio of t_2 and t_1 is always equal to the ratio of the distances of the respective grids from the cathode. This condition is taken as evidence of the absence of end effects. However, in argon and neon at moderate E/p and in gases at the lowest values of E/p, the bias required to reduce transmission to 5% of maximum transmission becomes comparable to the potential difference across the drift space. Under these conditions of large bias, the measured values of t_1 and t_2 and, to a lesser extent t_2-t_1, vary with the biasing voltage. Thus, it appears that the end effect reported previously is due to the use of too large a bias voltage.

Zero-Bias Operation

The zero-bias or rejection mode of operation of the grids is designed to reduce the perturbing effects of voltages applied to the grids by setting the dc bias voltage equal to zero and using only the pulsed voltage to collect some of the electrons near the grid. Thus the transmission of the grids is reduced and the current to the collector goes through a minimum when the gate is applied simultaneously with the arrival of the electrons at the grid. This mode of operation has the advantage that there is no voltage between grid wires during the period between pulses. The waveforms obtained with this type of operation are shown by the two upper curves of Fig. 2. Figure 2 shows that with equal pulse amplitudes the change in collector current is approximately the same for either method of operation and the computed drift velocities are equal to within experimental error. The final data at low E/p in He, Ne, H_2, and N_2 were obtained using this technique and the minimum usable pulse amplitudes. The measured values of t_1 and t_2 were found to be proportional to the respective drift distances. Accordingly, the results are believed to be free of end effects.

In all gases except argon the maximum transmission of the grids occurs at zero bias and the transmission decreases monotonically with increasing bias. Such a grid characteristic is shown by the dashed curve of Fig. 3 for hydrogen. The solid curves of Fig. 3 show the very unusual grid characteristics found for argon. For E/p values above 10^{-3} volt/cm-mm Hg the transmission increases with bias voltage to a maximum and then decreases as the bias is increased further. At an E/p of 10^{-3} volt/cm-mm Hg the transmission characteristic near zero bias changes from a minimum to a maximum which becomes sharper as E/p is

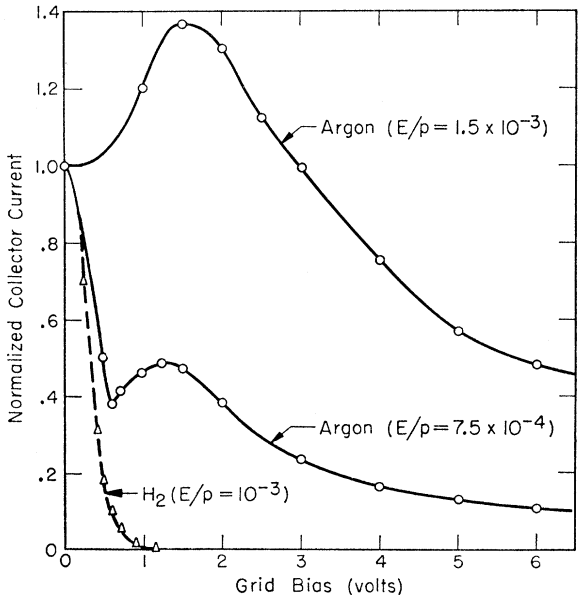

FIG. 3. Collector current as a function of dc grid bias voltage at various E/p. The two solid curves are for argon at 77°K and a normalized pressure of 746 mm Hg. Notice the maximum which occurs at a bias of 1.5 volts. This behavior is believed to be due to the local heating of the electrons in argon by the bias fields and the rapid variation of cross section with energy. The dashed curve shows a typical transmission curve for hydrogen for an E/p of 0.001 at 300°K at a pressure of 622 mm Hg. The curves obtained in helium, neon, and nitrogen were similar to the hydrogen curve.

decreased. As the bias voltage is increased, the transmission passes through a minimum and then a maximum. The structure in the grid characteristics found for argon is probably associated with the Ramsauer minimum in the argon scattering cross section but the effect has not been investigated in detail. The zero-bias method can be used with argon for $E/p<10^{-3}$ volt/cm-mm Hg. At higher E/p the bias was usually set for maximum transmission and the pulse amplitude adjusted to reduce the voltage between grid wires to zero.

III. APPARATUS

The experimental tube is essentially the same as described previously.[2] A ceramic terminal assembly was developed to replace the glass press. These terminals are easily repaired and provide better shielding and insulation of the electrical connections. The terminal end of the tube is enclosed in a second evacuated chamber in order to maintain high leakage resistance between the terminals and the flange and to reduce noise when the tube is operated in various liquid baths at temperatures different from room temperature. The grids were redesigned to improve their transmission characteristics. The grids used to obtain the data reported in this paper were 3-mil gold-plated molybdenum wires spaced 140 mils apart instead of 30 mils apart as reported in the previous paper.[2]

The pulsed light source used in these experiments was a hot-cathode hydrogen lamp[5] operated at peak currents of about 4.5 amperes with a duty cycle varying from 5 to 20%. The rise and fall times of the voltage pulses applied to the lamp and to the grids were approximately 0.2 microsecond.

The gas samples used in these experiments were Airco Assayed Reagent Grade. The manufacturer's mass spectrometric analysis shows that the impurity content of the argon, neon, helium, and nitrogen was less than 0.005 mole percent while the hydrogen contained 0.02 and 0.01 mole percent of nitrogen and hydrocarbons, respectively. The vacuum conditions before the admission of the gas were the same as described previously[2] so that the impurities introduced by the system were negligible. From the consistency of our results at fixed E/p and various pressures we conclude that contact potential differences between the grids were less than 0.05 volt. The pressure measurements[2] were made using oil and mercury manometers separated from the system with a null reading diaphragm type manometer having a sensitivity of at least 0.3 mm Hg. The voltage measurements were made with a voltmeter calibrated to better than 1% of the value read. Space charge distortion of the drift field is negligible at the currents used in these experiments, i.e., less than 10^{-11} ampere at the highest E/p and less than 10^{-13} ampere at the lowest E/p. Corrections to the drift velocity because of diffusion effects[4] were negligible for all the data reported.

Data were obtained at 77°K using a liquid nitrogen bath, at 195°K using a dry ice and acetone or alcohol bath, at 300±3°K using no bath, at 373°K using an oil bath heated by electric immersion type heaters. The temperature of the shell of the tube and of the cathode was measured with chromel-alumel thermocouples and found to be within 1°C of the bath temperature. In order to check for heating of the gas due to thermal radiation entering through the window when making measurements at 77°K in hydrogen, the cathode region was illuminated with a 250-watt infrared lamp. The measured drift velocity decreased by 1% while the gas pressure increased by 1%. These results are consistent with a gas temperature rise of about 3% or 2°C, in the measuring region and with the measured cathode temperature rise of 5°C. Since the normal cathode rise is less than 1°C above the bath temperature we believe that there is negligible rise in gas temperature due to heat flow through the window.

IV. RESULTS

The drift velocities of electrons in helium are shown as a function of E/p in Fig. 4. The values of E/p are expressed in units of volt/cm-mm Hg for an equivalent density at 300°K, i.e., $E/p=(E/N)3.22\times10^{16}$ for all data given in this paper. Here N is the gas density. The normalized pressures quoted are the values measured using the manometer system and multiplied by $300/T$. Data are shown for E/p values from 10^{-4} to 0.4 volt/cm Hg and temperatures of 77°K, 195°K, and 300°K. The normalized pressure varied from 98 mm Hg at high E/p and 300°K to 1240 mm Hg at very low E/p and 77°K. Drift velocities are shown only

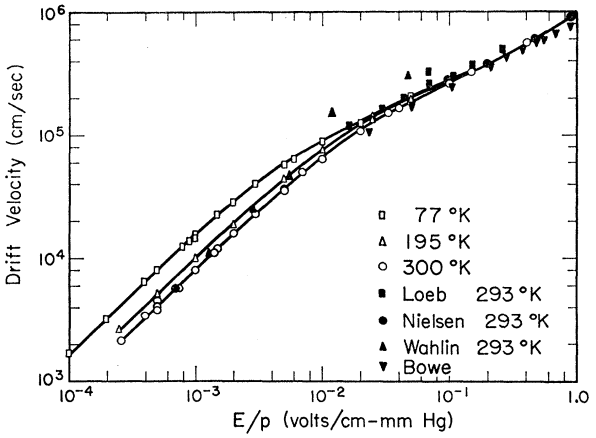

FIG. 4. Drift velocity of electrons in helium at 77°K, 195°K, and 300°K. The linear dependence of the drift velocity curve on E/p for $E/p<3\times10^{-4}$ volt/cm-mm Hg as evidenced by the 45° slope on the log-log plot indicates that the electrons are in thermal equilibrium with the gas.

[5] A. J. Allen and R. G. Franklin, J. Opt. Soc. Am. **29**, 453 (1939); and R. F. Weeks, J. Opt. Soc. Am. **49**, 429 (1959).

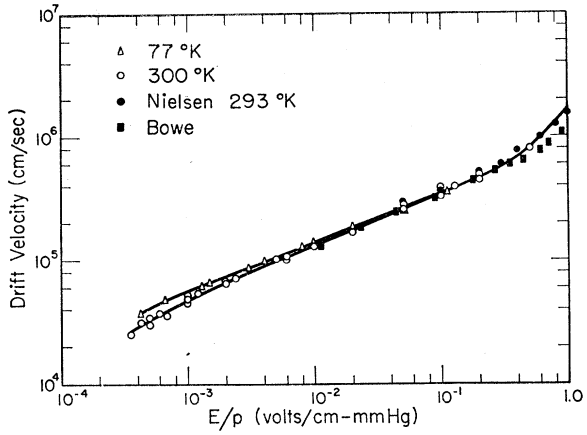

FIG. 5. Electron drift velocity in neon at 77°K and 300°K. Note that even at the lowest E/p at which there was a usable signal the variation of drift velocity is not a linear function of E/p so that we conclude the electrons are not in thermal equilibrium with the gas.

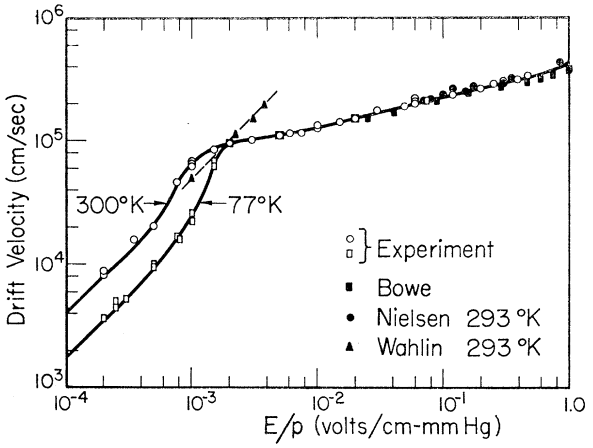

FIG. 6. Electron drift velocity in argon at 77°K and 300°K. The electrons are in thermal equilibrium with the gas for $E/p<4\times10^{-4}$ volt/cm-mm Hg.

for values of E/p such that the "time constant" for energy relaxation is much smaller than the drift time.[6] The results of Loeb[7] and Wahlin[8] for helium are shown by the solid squares and triangles, respectively. The agreement is good considering the difficulties of the early measurements. Very good agreement is obtained with Nielsen[9] over the common range of measurement but our results are significantly higher than those of Bowe.[10] The measured drift velocities shown in Fig. 4 for 300°K agree with those published previously[2] except for $E/p<10^{-2}$ volt/cm-mm Hg where the present values are about 15% larger. The helium drift velocities measured at 300°K with drift distances of 5.08 and 10.16 cm agreed to within experimental error with those obtained with the normal distances of 2.54 and 5.08 cm. We have not shown the drift velocities computed from the magnetic deflection experiments since the relationship between the drift velocity calculated from these experiments and that measured by time of flight experiments varies with the form of the electron velocity distribution and with E/p.[11]

The drift velocities of electrons in neon are shown in Fig. 5. Data are shown for E/p values from 4×10^{-4} to 0.5 volt/cm-mm Hg at 300°K using pressures between 48 and 660 mm Hg. Drift velocity data were also taken at 77°K at normalized pressures of 650 and 900 mm Hg. We were unable to obtain data at lower E/p at 300°K because the loss of electrons to the grid wires at the maximum available neon pressure was too large. Good agreement is obtained with Nielsen[9] over the common range of E/p. It is to be noted that at the lowest E/p the drift velocity is not a linear function of E/p as is the case for the other gases studied. This is due to the fact that the electrons have an energy distribution which is determined mainly by the electric field and not by the thermal motion of the gas atoms.[12]

[6] The "energy relaxation time" for an atomic gas in the absence of inelastic collisions is roughly equal to $M(2m\bar{\nu})^{-1}$, where M and m are the atomic and electronic masses and $\bar{\nu}$ is an average electron collision frequency. Approximate values for A, Ne, and He are $500/p$, $100/p$, and $5/p$ μsec, respectively, at the E/p values of interest. Estimates of this time for molecular gases must include the effects of rotational and vibrational excitation. Average values for H_2 and N_2 are about 1/10 that for He.

[7] L. B. Loeb, Phys. Rev. **23**, 157 (1923); and **19**, 24 (1922).

[8] H. B. Wahlin, Phys. Rev. **37**, 260 (1931); **27**, 588 (1926); and **23**, 169 (1924).

[9] R. A. Nielsen, Phys. Rev. **50**, 950 (1936).

[10] J. C. Bowe, Phys. Rev. **117**, 1411 and 1416 (1960). Unfortunately, this author, along with many others, reports data for only one drift distance so that end effects and waveform distortion due to an unsymmetrical light pulse cannot be eliminated as source of error.

[11] These experiments are summarized by R. H. Healey and J. W. Reed, *The Behavior of Slow Electrons in Gases* (The Wireless Press, Sidney, 1941). The drift velocity computed using Eq. (17) of this reference is exact when the electron collision frequency is independent of electron energy; it has been shown to be 6% high when the collision cross section is independent of energy and when the only important terms in the Boltzmann equation are the energy gain from the electric field and the energy loss in elastic scattering collisions. See W. P. Allis and H. W. Allen, Phys. Rev. **52**, 703 (1937). At very low E/p, the distribution function becomes Maxwellian and the drift velocity computed from the magnetic deflection experiments is expected to be 18% high when the collision cross section is constant. We are unable to explain the much larger difference between our results and those of Townsend and Bailey at low E/p in helium. See Fig. 6 of reference 2.

[12] If we assume that the elastic scattering cross section is independent of energy, the condition for a 10% increase in electron energy due to the electric field for atomic gases is that $E/\sigma N=0.1\times(6m/M)^{\frac{1}{2}}(kT/e)$, where M is the mass of the atom and the remaining symbols are defined in the text. See, for example, M. J. Druyvesteyn and F. M. Penning, Revs. Modern Phys. **12**, 87 (1940), Sec. 4. According to this relation the excess of the average electron energy over thermal is less than 10% at 300°K for E/p below 1.5×10^{-3}, 10^{-4}, and $\sim10^{-4}$ volt/cm-mm Hg for helium, neon, and argon, respectively. A more accurate calculation for argon (see reference 24) shows that the average electron energy is within 10% of thermal for E/p less than 2.4×10^{-4} and 3.3×10^{-4} volt/cm-mm Hg at 300°K and 77°K, respectively. Estimates of the limiting values of E/p are difficult for the molecular gases because of our lack of knowledge concerning inelastic collisions between electrons and gas molecules.

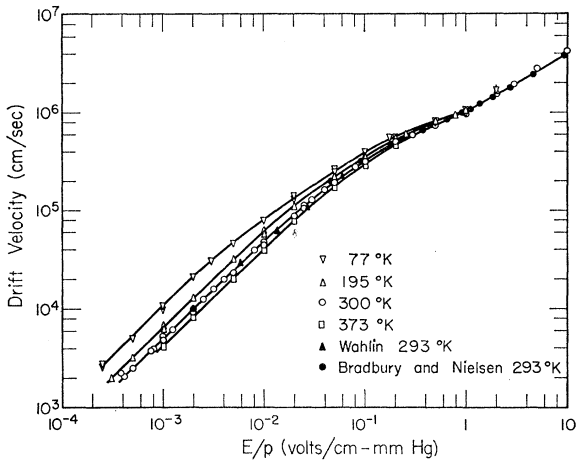

FIG. 7. Electron drift velocity as a function of E/p in hydrogen at 77°K, 195°K, 300°K, and 373°K. For $E/p<3\times10^{-3}$ the electrons are in thermal equilibrium with the gas at each temperature.

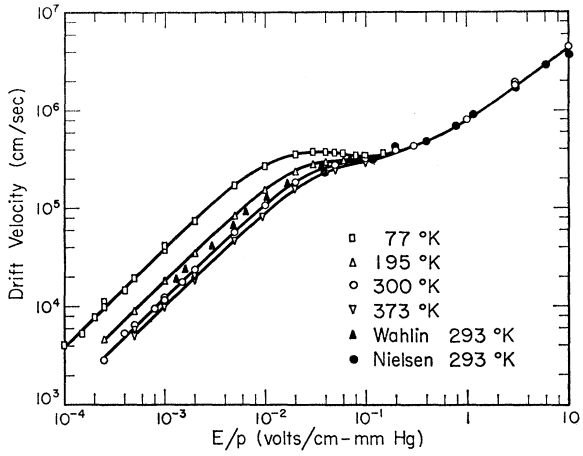

FIG. 8. Electron drift velocity as a function of E/p in nitrogen at 77°K, 195°K, 300°K, and 373°K. For $E/p<3\times10^{-3}$ the electrons are in thermal equilibrium with the gas at each temperature. Notice the shallow minimum in the 77°K curve which is due in part to the variation of the elastic collision cross section with electron energy.

The drift velocities for electrons in argon are shown in Fig. 6. Data are shown for E/p from 2×10^{-4} to 0.5 volt/cm-mm Hg at 77°K and 300°K. The pressures used in the 300°K measurements varied from 735 mm Hg at the lowest E/p to 151 mm Hg at the highest E/p. At 77°K the pressure was the equilibrium vapor pressure over solid argon. The drift velocities of electrons were found to be independent of gas temperature for values of E/p greater than 2×10^{-3} volt/cm-mm Hg. Drift velocities are shown only for values of E/p well below that at which the time constant for energy relaxation equals the transit time.[6] The measured drift velocities are within 10% of those obtained by Nielsen,[9] by Colli and Facchini,[13] by Kirshner and Tofollo,[14] and by Bowe[10] over the common range of E/p. These results are about 20% below those of Bortner, Hurst, and Stone,[15] The still larger drift velocities measured by Klema and Allen[16] and English and Hanna[16] for E/p of 0.2 volt/cm-mm Hg and above have been attributed to impurities.[10,13–15] The drift velocities measured by Wahlin[8] for argon containing 1.5% nitrogen at low E/p are shown by the solid triangles. These results are in very good agreement with unpublished data obtained in our experiments for similar concentrations of nitrogen in argon. Note that an extension of the dashed line through Wahlin's data passes very close to our low E/p data, i.e., the low E/p values for the electron mobility from the two experiments are in good agreement. Because of the large energy lost to nitrogen as a result of rotational excitation the maximum E/p for which the electrons are in thermal equilibrium is much greater for the mixture than for pure argon.[12]

The drift velocities of electrons in hydrogen for E/p values from 2.5×10^{-4} to 10 volt/cm-mm Hg at 77°K, 195°K, 300°K, and 373°K are shown in Fig. 7. The normalized pressures used varied from 26 to 1290 mm Hg at 77°K and from 5 to 660 mm Hg at 300°K. Good agreement is obtained with Bradbury and Nielsen[1] and with Wahlin[8] over the range of E/p common to the respective measurements.

The drift velocities of electrons in nitrogen for E/p values from 10^{-4} to 10 volt/cm-mm Hg at 77°K, 195°K, 300°K, and 373°K are shown in Fig. 8. The normalized pressures used were 700 and 1200 mm Hg at 77°K and varied from 2 to 745 mm Hg at 300°K. In the common range of E/p our results are in good agreement with those previously reported by Nielsen,[9] Colli and Facchini,[13] and Klema and Allen,[16] and about ten percent higher than those of Bortner, Hurst, and Stone,[15] and of Bowe.[10] At very low E/p our room temperature values are about 20% below those of Wahlin[8] and 10 to 12% higher than the values which we reported previously.[17]

The drift velocities given above for argon, helium, nitrogen, and hydrogen at very low E/p are directly proportional to E/p and vary appreciably with the gas temperature. We believe that at the lowest values of E/p the electrons are essentially in thermal equilibrium with the gas so that the distribution of electron velocities is Maxwellian and is characterized by a temperature equal to the gas temperature.[12]

[13] L. Colli and U. Facchini, Rev. Sci. Instr. **23**, 39 (1952).
[14] J. M. Kirshner and D. S. Toffolo, J. Appl. Phys. **23**, 594 (1952).
[15] T. E. Bortner, G. S. Hurst, and W. G. Stone, Rev. Sci. Instr. **28**, 103 (1957).
[16] E. D. Klema and J. S. Allen, Phys. Rev. **77**, 661 (1950), and W. N. English and G. C. Hanna, Can. J. Phys. **31**, 768 (1953).
[17] A. V. Phelps and J. L. Pack, Phys. Rev. Letters **3**, 340 (1959). Note that a minus sign was omitted from the expression σ_i in footnote 5 of this letter.

V. ANALYSIS OF DATA

In order to obtain momentum transfer cross sections as a function of electron energy from these measurements of electron drift velocity we must know the electron energy distribution. Even though no inelastic collisions occur in the rare gases in the E/p range covered, the energy distribution is known *a priori* only in the lower E/p range where the electrons are in thermal equilibrium with the gas.[12] Therefore, in this paper use will be made only of the lower portions of the curves of drift velocity versus E/p where the drift velocity varies linearly with E/p and the electrons have an energy distribution the same as that of the gas. To obtain the cross sections we make use of the integral relations between the drift velocity and collision frequency.

The drift velocity, w, of electrons in the presence of a dc electric field, E, is given by[18,19]

$$w=(\mu N)(E/N)=\frac{4\pi}{3}\frac{e}{m}\left(\frac{E}{N}\right)\int_0^\infty f_0\frac{d}{dv}\left(\frac{v^3N}{\nu}\right)dv, \quad (1)$$

where μ is the electron mobility, e and m are the electronic charge and mass, f_0 is the spherically symmetrical term in the expansion of the electron velocity distribution, v is the electron velocity, ν is the frequency of momentum transfer collisions, and N is the gas density. Assuming a power series representation of N/ν in terms of electron velocity,[20] we have

$$N/\nu=(\sigma v)^{-1}=\sum b_j v^{-j}, \quad (2)$$

where σ is the cross section for momentum transfer collisions. The negative sign of j is chosen so that Eq. (2) is consistent with the corresponding equation of reference 20. For low E/p the electrons are in thermal equilibrium with the gas and

$$f_0=(m/2\pi kT)^{\frac{3}{2}}\exp(-mv^2/2kT),$$

where T is the gas temperature. Upon substitution of Eq. (2) into Eq. (1) and integration, we have

$$\mu N=\frac{e}{m}\sum_j\frac{(3/2-j/2)!}{(3/2)!}b_j\left(\frac{2kT}{m}\right)^{-j/2}=\sum_j B_j\left(\frac{2kT}{m}\right)^{-j/2}, \quad (3)$$

[18] W. P. Allis, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1956), Vol. 21, p. 413, Eq. (31.9).

[19] This expression is also obtained by setting $\omega=0$ in the formula for the ac mobility of electrons in a gas. See H. Margenau, Phys. Rev. **69**, 508 (1946). It should be noted that the alternative expression developed by E. A. Desloge, S. W. Matthyss, and H. Margenau, Phys. Rev. **112**, 1437 (1958) gives coefficients similar to those of Eq. (3) but divided by a factor of $(3-j)/3$. We can decide between these two expressions experimentally. Thus, the collision cross sections for nitrogen determined from the present experiments and from the microwave experiments of reference 20 using the generalized form of Eq. (1) agree to within 15%. If we use the alternative expression, the derived cross sections disagree by 40%.

[20] A. V. Phelps, O. T. Fundingsland, and S. C. Brown, Phys. Rev. **84**, 559 (1951).

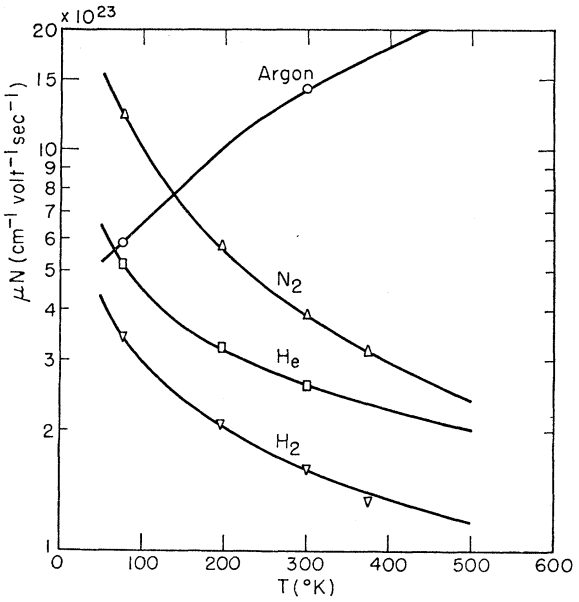

FIG. 9. The solid curves show the temperature dependence of the power series expansions chosen to approximate the measured values of μN. The curve shown for argon is that which leads to the σ_1 curve of Fig. 11.

where we use the notation $(3/2)!\equiv\Gamma(5/2)$. Here $(2kT/m)^{\frac{1}{2}}$ is the most probable speed for a Maxwellian distribution of velocities having a temperature equal to the gas temperature. From experiment we have the quantity μN at several temperatures. We can, therefore, choose a reasonable set of values of j and determine the coefficients from the experimental data. Comparing Eq. (3) with Eq. (2), we see that the cross section is given by

$$\sigma^{-1}=\frac{m}{e}\sum_i\frac{(3/2)!}{(3/2-j/2)!}B_j v^{1-j}. \quad (4)$$

We note that if the cross sections were constant we

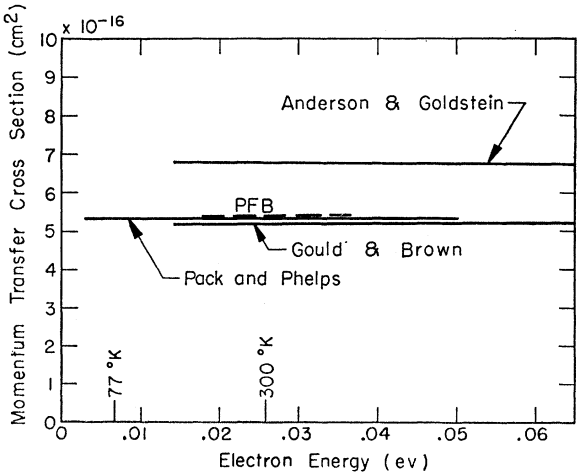

FIG. 10. Momentum transfer cross section as a function electron energy in helium.

would have the $j=+1$ term only and μN would vary as $(2kT/m)^{-\frac{1}{2}}$. For helium this is a good assumption but for argon, hydrogen, and nitrogen the cross sections must be assumed to depend upon v.

The experimentally determined values of $\mu N = wN/E$ for $E/p \rightarrow 0$ from the data of Figs. 4–8 are given in Table I and are plotted as points in Fig. 9. The solid curves are plots of the power series chosen to approximate the temperature dependence of the measured μN values.

The measured values of μN for helium were fitted to a single term power series with $j=+1$ to obtain a velocity-independent cross section equal to 5.3×10^{-16} cm^2. This cross section is shown in Fig. 10, along with the cross sections obtained previously. The present results are in good agreement with those of Phelps, Fundingsland, and Brown (PFB)[20] and of Gould and Brown[21] obtained from an analysis of microwave measurements of the electron mobility, and 25% below the results of Anderson and Goldstein.[22] Note that the method presented in this paper gives the values of cross sections as functions of electron energy

TABLE I. Experimental values of μN obtained at low E/p (values of μN in cm^{-1} volt^{-1} sec^{-1}).

T°K	Argon	Helium	H_2	N_2
77	5.8×10^{23}	5.15×10^{23}	3.41×10^{23}	13.0×10^{23}
195		3.22×10^{23}	2.06×10^{23}	5.70×10^{23}
300	14.2×10^{23}	2.58×10^{23}	1.60×10^{23}	3.86×10^{23}
373			1.34×10^{23}	3.15×10^{23}

only in the range from roughly 0.003 to 0.05 ev. On the basis of the good fit of theory and experiment which we obtained previously[2] for E/p values between 0.1 and 1.0 using a cross section of 6.2×10^{-16} cm^2, we conclude that the cross section increases by about 20% as the electron energy increases from 0.003 ev to about 1 ev. This result is in good agreement with the results of Gould and Brown[21] but is inconsistent with the results of Bowe.[10]

Figure 9 shows that for a fourfold increase in argon temperature μN increases by a factor of 2.4 so that the largest $|j|$ in Eq. (4) must be greater than 1. We can evaluate only a 2-term power series expansion since μN values were obtained at two temperatures. Three possible series are those with $j=+1$ and -2, giving σ_1; $j=+1$ and -3, giving σ_2; and $j=-1$ and -2 giving σ_3. Evaluating the constants by the above method we find the cross section as shown in Fig. 11. It has been suggested by Varnerin[23] that the validity of these calculations is greatest where the values are independent of the choice of the power series, in other

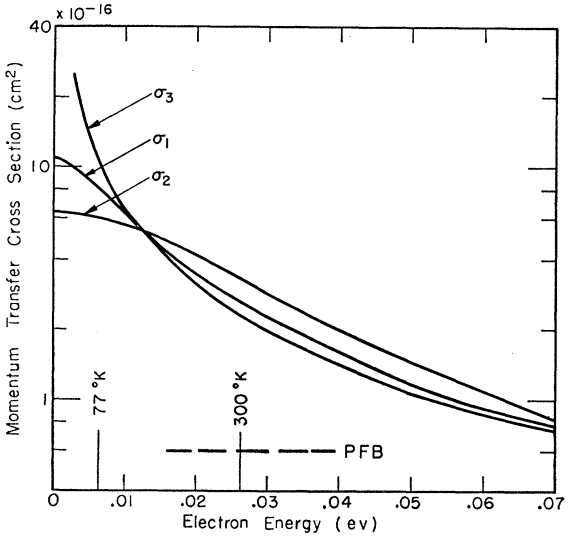

FIG. 11. Momentum transfer cross sections in argon as a function of electron energy for three choices of the power series expansion of N/v. The curves cross at electron energies of 0.013 and 0.08 ev and, according to Varnerin, are most accurate at these energies. Note that the cross section is plotted on a logarithmic scale.

words, where σ_1, σ_2, σ_3 cross. The curves cross at about 0.013 and 0.08 ev. These crossings occur at energies which are below that of Ramsauer minimum in argon which occurs at a few tenths of an ev.[24] These curves indicate that the microwave value reported by Phelps, Fundingsland, and Brown[20] was obtained for electrons which were not in thermal equilibrium with the gas. Evaluations of the drift velocity data including the nonthermal region have been carried out by Bowe[10] and by Frost and Phelps.[24]

In hydrogen the derived cross section can be represented by $\sigma^{-1}=(1.28-2.17u)\times10^{15}$ cm^{-2}, where u is the electron energy in ev, and is shown in Fig. 12.

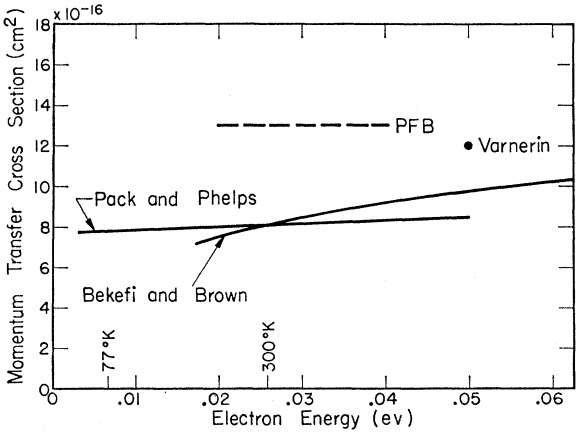

FIG. 12. Momentum transfer cross section as a function of electron energy in hydrogen.

[21] L. Gould and S. C. Brown, Phys. Rev. **95**, 897 (1954). See also J. L. Hirshfield and S. C. Brown, J. Appl. Phys. **29**, 1749 (1958).

[22] J. M. Anderson and L. Goldstein, Phys. Rev. **102**, 933 (1956).

[23] L. J. Varnerin, Jr., Phys. Rev. **84**, 563 (1951).

[24] L. S. Frost and A. V. Phelps, Bull. Am. Phys. Soc. **5**, 371 (1960).

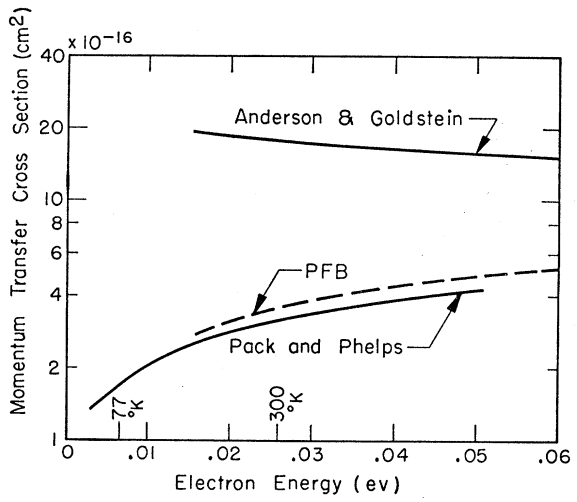

FIG. 13. Momentum transfer cross section as a function of electron energy in nitrogen. Note that the cross section is plotted on a logarithmic scale. The temperatures indicated are the electron volt equivalents of kT.

These values are about $\frac{2}{3}$ of the cross section previously reported by Phelps, Fundingsland, and Brown[20] and by Varnerin.[23] The magnitude of this cross section for the common energy range is in good agreement with the results of Bekefi and Brown[25] but the cross section obtained from the present experiments varies much less rapidly with energy.

The cross section in nitrogen as obtained by this method is given by $\sigma^{-1}=5.31\times10^{14}u^{-\frac{1}{2}}-3.15\times10^{11}u^{-\frac{3}{2}}$ cm^{-2} and is shown in Fig. 13. It agrees with the value of Phelps, Fundingsland, and Brown[20] within about 10% but is about a factor of five below that of Anderson and Goldstein[26] at 0.026 ev. The σ values reported previously by Phelps and Pack[17] are 10–12% higher.

In principle we could compare the present results with the low-energy cross sections obtained from studies for the shift and the broadening of the higher alkali atom spectral lines.[27] However, Baranger[28] has pointed out that the usual assumption that these cross sections apply to zero-energy electrons is incorrect since the average electron wavelengths correspond to energies of the order of a few hundredths of an electron volt. Comparison of the two experiments will have to await a better understanding of the spectral observations. In view of the limited range of energy covered by the present analysis, we have not attempted to compare the derived cross sections with the result of theoretical calculations. The comparison has recently been carried out by Bowe[10] and by Kivel.[29]

[25] G. Bekefi and S. C. Brown, Phys. Rev. **112**, 159 (1958).
[26] J. M. Anderson and L. Goldstein, Phys. Rev. **100**, 1037 (1955); and **102**, 388 (1956).
[27] H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Oxford University Press, London, 1952), p. 178.
[28] M. Baranger (private communication).

V. SUMMARY

Electron drift velocities in atomic and molecular gases measured at very low E/p have been used to obtain the cross sections for momentum transfer collisions in the energy range from 0.003 to 0.05 electron volt. The techniques described in this paper make possible measurements at energies not available with present beam experiments so that one is willing to put up with the lack of energy resolution. An inherent advantage of the techniques used here is the lack of contamination due to a hot filament or to discharge products.

The drift velocity data for electrons at the higher E/p values can be analyzed to obtain cross sections as a function of energy for energies well above thermal. This requires the solution of the Boltzmann equation for the electron energy distribution appropriate to the higher fields including inelastic collisions in the case of molecular gases. Approximate solutions have been obtained by Bekefi and Brown[25] and by Bowe[10] under the assumption that the inelastic scattering cross section is a slowly varying function of energy. Since this assumption fails near threshold, Frost and Phelps have made calculations using more accurate forms for the excitation cross section in hydrogen.[30] These will be presented in detail in a later publication.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for valuable discussion of this work with their associates in the Atomic Physics Group.

[29] B. Kivel, Phys. Rev. **116**, 926 (1959).
[30] L. S. Frost and A. V. Phelps, Bull. Am. Phys. Soc. **5**, 122 (1960).