Electron Drift and Diffusion Measurements in H₂ and D₂ with Crossed Electric and Strong Magnetic Fields*†

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In a strong magnetic field, the cyclotron frequency of the electron is much larger than the elastic-collision frequency with neutral molecules ($\omega_b^2 \tau^2 \gg 1$). Expressions derived from the Boltzmann equation for the energy distribution, drift velocities, and diffusion coefficients in crossed electric (E) and magnetic (B) fields are simplified in the limit of a strong magnetic field, with the average electron energy a function of E/B. Experiments were done in a coaxial cylindrical geometry with E perpendicular to B. Measurements of the ratio of the perpendicular ($E \times B$) to transverse (E) drift velocities in the range $12 < \omega_b \tau < 48$, and of diffusion parallel to B in the range $3 < \omega_b \tau < 8$, showed that the average energy is a function only of E/B, the perpendicular drift velocity. Curves were obtained for hydrogen, deuterium, and helium which give the transverse drift velocity in terms of the parameters E/B (cm/sec) and B/p (kG/mm Hg at 20°C). Comparison of drift velocity and diffusion measurements with theoretical expressions yielded a momentum-transfer cross section for H₂ which is 10 to 20% larger, in the range of 0.3 to 4 eV, than that obtained by other authors. Average electron energies of 0.3 to 4.5 eV were determined for hydrogen and deuterium as a function of E/B which ranged from 10^6 to 10^7 cm/sec; proper comparison with average energies measured as a function of E/p with $B = 0$ shows good agreement. The inelastic, molecular-excitation energy losses in H₂ are about twice those in D₂.

1. INTRODUCTION

TO the author's knowledge, no previous measurements have been reported on electrons moving through a gas with a strong magnetic field B perpendicular to a steady electric field E. A strong magnetic field (SMF) is defined as one where the cyclotron frequency of electrons, $\omega_b = eB/m$ (e and m are the charge and mass of an electron), is much greater than the elastic-collision frequency ν_c of the electrons with the gas molecules. The ratio of these frequencies forms an important parameter denoted by $\omega_b/\nu_c = \omega_b \tau$ and the SMF limit is defined when $(\omega_b \tau)^2 \gg 1$. Theoretical expressions for the energy distribution, drift velocities, and diffusion coefficients are greatly simplified in the strong-field limit.

An extensive amount of work has been reported on electron motion in a gas with an applied electric field only.[1] For these conditions, it has been shown that the parameter determining the average energy is E/p, where p is the gas pressure. In the SMF limit it is shown theoretically that the average energy is a function of E/B. Furthermore in this limit the energy distribution theoretically is Maxwellian independent of the elastic-collision cross section.

Previous experiments measuring the drift velocity have been of three types: magnetic-deflection,[2,3] electron-shutter,[4,5] and pulse techniques.[6] The magnetic-deflection method was the easiest to use in the present coaxial cylindrical geometry. Previous diffusion experiments measured directly the ratio of the mobility to diffusion coefficients, which is a determination of the average energy.[7] This is possible for $B = 0$ because the diffusion is isotropic; however the diffusion is not isotropic in the presence of a magnetic field. The present work measures the diffusion along B. Results of the drift velocity and diffusion measurements are combined

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[1] L. B. Loeb, *Basic Processes of Gaseous Electronics* (University of California Press, Berkeley, California, 1955).

[2] R. H. Healey and J. W. Reed, *The Behavior of Slow Electrons in Gases* (The Wireless Press, Sidney, Australia, 1941).

[3] L. G. H. Huxley and A. A. Zaazou, Proc. Roy. Soc. (London) A196, 402 (1949).

[4] N. E. Bradbury and R. A. Nielsen, Phys. Rev. 49, 388 (1936).

[5] J. L. Pack and A. V. Phelps, Phys. Rev. 121, 798 (1961).

[6] J. A. Hornbeck, Phys. Rev. 83, 374 (1951).

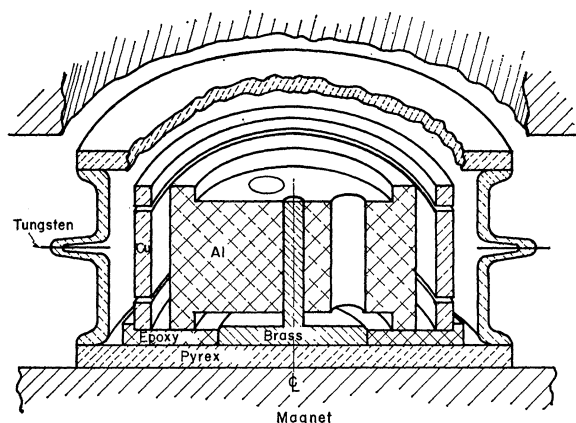[7] J. S. Townsend and V. A. Bailey, Phil. Mag. 42, 873 (1921).

FIG. 1. General electrode structure in the glass vacuum chamber. The unit rests flat on bottom magnet pole.

to yield a value for the collision cross section and the average energy as a function of E/B.

2. THEORY

From the Boltzmann equation, an expression has been derived for the spherically symmetric part of the distribution function based only on elastic collisions of electrons with neutral molecules (gas temperature assumed zero)[8]:

$$\ln f^0 = -3[m^3/M(eE)^2]\int (\nu_c{}^2+\omega_b{}^2)v\,dv, \quad (1)$$

where v is the electron velocity, and M is the molecular mass. In the SMF limit, this expression reduced to $f^0 = \exp(-av^2)$, where $a = 3\eta mB^2/2ME^2$, and the average-energy-loss-per-collision parameter η has been introduced to account for inelastic collisions. When elastic collisions alone determine the distribution, η is unity. It is assumed here that the inelastic collisions do not alter the distribution, but only decrease the average energy. The parameter η is defined by $\eta = \lambda M/2m$, where λ is the average fractional energy loss per collision.

Expressions for the transverse (E) drift velocity v_T and the perpendicular (E×B) drift velocity $v_\perp$ have been derived[9,10]:

$$v_T = \frac{4\pi}{3n_g}\frac{eE}{m}\int_0^\infty \frac{\nu_c}{(\nu_c{}^2+\omega_b{}^2)}\frac{\partial f^0}{\partial v}v^3\,dv, \quad (2)$$

$$v_\perp = \frac{4\pi}{3n_g}\frac{eE}{m}\int_0^\infty \frac{\omega_b}{(\nu_c{}^2+\omega_b{}^2)}\frac{\partial f^0}{\partial v}v^3\,dv, \quad (3)$$

where n_g is the gas density.

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[8] W. P. Allis and H. W. Allen, Phys. Rev. **52**, 703 (1937).

[9] W. P. Allis, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1956), Vol. XXI, p. 404.

[10] L. G. H. Huxley, Australian J. Phys. **10**, 240, 118 (1957).

In the SMF limit (using the SMF value for f^0), Eq. (3) and the ratio of (2) to (3) reduce to

$$v_\perp = FE/B \quad (4)$$

and

$$\omega_b/R_v = (8a^{5/2}/3\pi^{1/2})\int_0^\infty \nu_c e^{-av^2}v^4\,dv. \quad (5)$$

Here we have introduced the perpendicular-to-transverse drift-velocity ratio, $R_v = v_\perp/v_T$. Note that if ν_c is constant, then we have $\omega_b\tau/R_v = 1$. The factor F in Eq. (4) is unity in the SMF limit and has been introduced to make the results applicable in the moderate-field region. When the magnetic field is only moderately strong ($\omega_b\tau > 3$), we can see from Eq. (2) and (3) that the drift velocities are each reduced by approximately $(\omega_b{}^2\tau^2)/(1+\omega_b{}^2\tau^2)$. Since to a good approximation $\omega_b\tau$ is equal to R_v, the correction factor is defined as $F = R_v{}^2/(1+R_v{}^2)$. This correction factor cancels out in Eq. (5) when the ratio of drift velocities is taken.

Similarly, the expressions given by Allis[9] for the parallel $(D_{||})$, transverse (D_T), and perpendicular $(D_\perp)$ components of the diffusion tensor reduce in the SMF limit to

$$D_{||} = (4a^{3/2}/3\pi^{1/2})\int_0^\infty \nu_c{}^{-1}v^4 e^{-av^2}\,dv, \quad (6)$$

$$D_T = (4a^{3/2}/3\pi^{1/2})\omega_b{}^{-2}\int_0^\infty \nu_c v^4 e^{-av^2}\,dv, \quad (7)$$

and

$$D_\perp = (2a\omega_b)^{-1}. \quad (8)$$

3. APPARATUS

A coaxial cylindrical geometry was used to eliminate edge effects in the E×B direction and to align the electrodes accurately with the magnetic field. The anodes were stacks of copper rings aligned by epoxy
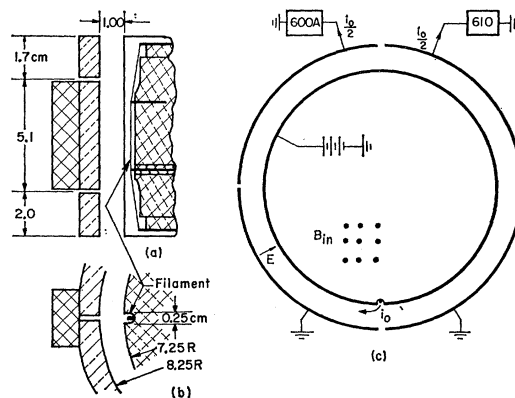

FIG. 2. Experimental details for measuring the drift-velocity ratio. (a, b) Anode construction (epoxy blocks and pins hold quadrants together) and location of filamnt on cathode. Only the central portion of the filament is heated. (c) Electrical schematic for measuring the ratio (shown for $R_v = 24$). The currents were measured with Keithley 600A and 610 electrometers.

FIG. 3. Ratio of the magnetic field to pressure reduced to R_v = 12.15 as a function of E/B, the perpendicular drift velocity. The data in hydrogen taken at 20°C.
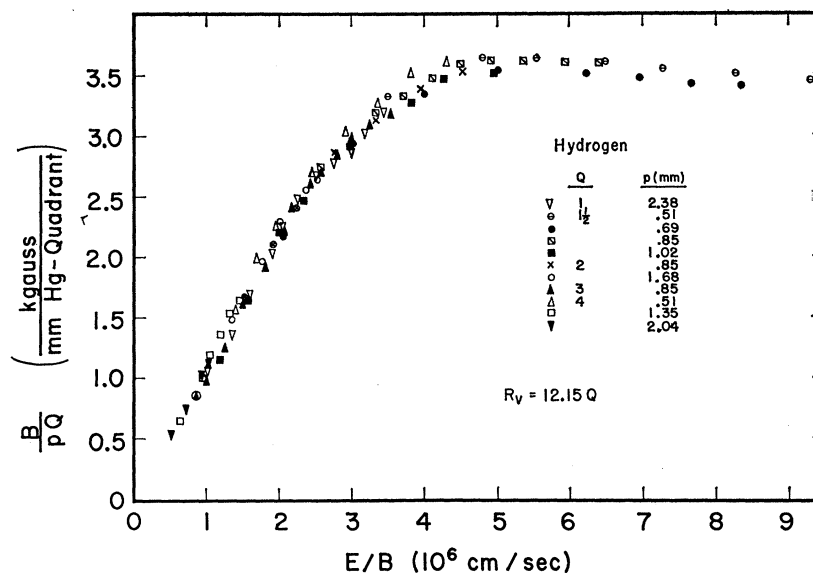
pegs through the rings; the cathodes were aluminum cylinders. The electrodes were centered coaxially with an epoxy-brass base as shown in Fig. 1. With a gap separation of 1 cm and a median electrode radius of 7.75 cm, the electric field was sufficiently constant across the gap. The cylindrical Pyrex vacuum chamber (which fits in the 12.5-cm gap between the 45-cm-diam poles of a magnet) was enclosed top and bottom with flat end plates having ground-glass joints sealed with vacuum grease. An oil-diffusion pump and liquid-nitrogen trap evacuated the unbakeable system to a base pressure of 4 to 6×10^{-5} mm Hg. In use, the system was operated statically with the cold trap pumping on the condensible impurities so that the impurity level was less than 0.1% of the gas pressure. Standard tanks of hydrogen, deuterium, and helium were used for gas supplies. In hydrogen, the elastic cross section and energy losses are sufficiently large that small amounts of impurities will not affect the measurements described here. Electron currents to the anode were measured with two electrometers (Keithley 600A and 610) which have negligible voltage drops. Contact potentials were negligible. Strings of batteries gave cathode potentials up to 315 V.

4. DRIFT-VELOCITY MEASUREMENTS

Details and dimensions of the electrode structure for measuring the drift-velocity ratio R_v are shown in Fig. 2. The middle anode ring is split into four quadrants in the azimuthal direction. A hot tantalum filament, mounted parallel to the magnetic field in a slot on the cathode, emitted a line source of electron current i_0. The ratio R_v was taken as the average distance that the electrons traveled in the perpendicular (azimuthal) direction divided by the electrode gap (with these electrodes, R_v is 12.15 Q where Q is the number of quadrants traversed).

At a given pressure and electric field, the magnetic field was adjusted so that the current i_0 was divided equally between two adjacent quadrants. Figure 2(c) shows the electrical schematic for measurements with $Q=2$. The measurements were repeated after evacuating and refilling the chamber, and the two sets of data were averaged (reproducibility within 2%). Space-charge effects were negligible, since the total current to the anode was about 10^{-10} A. Since air was the chief impurity in the tank hydrogen,[11] the effect of adding 1 to 2% air to the gas in the chamber was tested; no measureable difference was observed.

The parameters R_v, p, E, and B ranged, respectively, from 12.15 to 48.6, 0.5 to 4 mm Hg, 22.5 to 315 V/cm, and 1.7 to 9 kG. The random errors on these parameters were less than 1%. One consistent error of less than 1% came from the electrons being captured when they were theoretically still a cyclotron radius from the anode. The largest experimental error most likely came from transverse diffusion of the electrons, which caused the measured drift velocity ratio to be smaller than it theoretically should be. Those electrons that diffuse toward the anode are captured sooner than they theoretically should be, and additional diffusion causes some of the remaining electrons to be shifted toward the anode. Estimates on the magnitude of this error computed from the expression for the transverse-diffusion coefficient, Eq. (7), and the measured drift time place the error at less than 5%. Also, any effect due to diffusion should be pressure-dependent, and I observed no such dependence in H_2 or D_2. Direct measurement of the transverse-drift velocity, such as by light-pulse techniques, is needed to check the present results.

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[11] The tank of H_2 was analyzed with a mass spectroscope and only air was noticeable, 0.04% O_2 and 0.19% N_2.
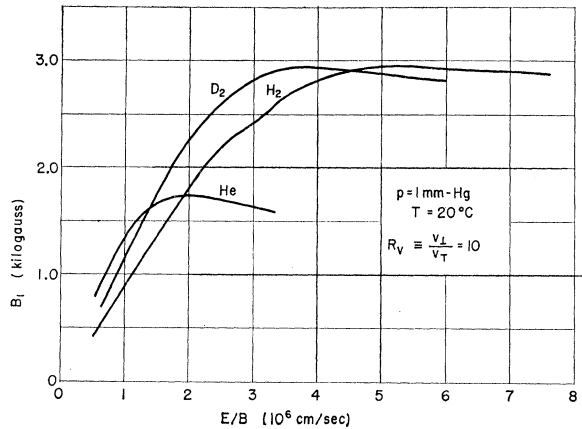
FIG. 4. Magnetic field B_1 as a function of E/B needed to produce a drift-velocity ratio $R_v=10$ at 1 mm Hg and 20°C in hydrogen, deuterium, and helium.

In the SMF limit of the theory, the average electron energy is a function of E/B, and at a given average energy R_v is proportional to B/p. By reducing all data for a given gas to a common value of R_v, one can compare the data by plotting B/pQ as a function of E/B. In other words, for a given average energy of the electrons, a certain value of B/p is needed to produce a predetermined ratio of drift velocities. All the data taken in hydrogen are shown in Fig. 3. The results for deuterium were equally good in having the data fall on a smooth curve. Data taken in helium did not fall so smoothly on a curve except at the higher pressures, which shows that the effect of transverse diffusion was observable. The drift velocity E/B is expressed in cm/sec and the parameter B/pQ is expressed in kG/mm Hg quadrant. The gas temperatures in the measurements ranged from 19 to 25°C, but the data were adjusted to correspond to a temperature of 20°C.

Smooth curves were determined by best-fitting the drift-velocity data. These curves (Fig. 4) are plots of an effective magnetic field B_1 as a function of E/B. Here, B_1 is the magnetic field at 1 mm Hg and 20°C, which makes $R_v=10$ at a given E/B. The transverse drift velocity is obtained from these curves in terms of the parameters E/B and B/p expressed in the units of E in V/cm, B in kG, and p in mm Hg. In these units, the perpendicular drift velocity in cm/sec is [from Eq. (4)]

$$v_\perp = 10^5 FE/B. \qquad (9)$$

The drift-velocity ratio is given by $R_v=10 \; B/pB_1$. Thus the transverse drift velocity is given in cm/sec by

$$v_T = 10^4 FB_1(p/B)(E/B). \qquad (10)$$

Recall from Sec. 2 that $F=1$ in the SMF limit.

5. PARALLEL-DIFFUSION EXPERIMENT

Measurements of the diffusion in the perpendicular direction would be very difficult to interpret because of the complicated nature of the diffusion tensor.[9] For that reason, diffusion in the parallel direction was measured. The general electrode structure and vacuum system are the same as described for the drift-velocity experiment and details of the electrodes are given in Fig. 5(a). Cathode electron emission came from a hot tungsten filament located behind a slit perpendicular to the magnetic field. Two experimental problems became very troublesome in a SMF. First, care had to be taken that emitted electrons did not diffuse along the magnetic field and around the top of the cathode. Also the slit width (0.10 cm) had to be larger than the thickness of the cathode material (0.018 cm) on either side of the slit. This was necessary so that sufficient electrons could escape through the slit without raising the filament temperature so high that large numbers of impurities would be boiled off or large numbers of negative ions formed.

The experimental procedure consisted of simultaneously reading the current to the center ring and the sum of the currents to the side rings with two electrometers as shown in Fig. 5(b). At a given pressure and electric field, the magnetic field was adjusted until a predetermined ratio of 70% of the current was going to the central ring. After the chamber was evacuated and refilled, the measurements were reproducible to within 2%. For hydrogen and deuterium, the parameters p, E, and B ranged respectively from 1.7 to 4.0 mm Hg, 6 to 270 V/cm, and 0.8 to 7 kG. The total current to all rings was about 10^{-11} A, so that space charge can be neglected.

Diffusion in the helium could not be measured in a SMF because huge numbers of negative ions were emitted, due most likely to impurities in the gas. These ions were detected by increasing the magnetic field. As B increases, a larger fraction of the emitted electrons diffuse to the side rings. But at very large fields, very few electrons escape through the emission slit, because
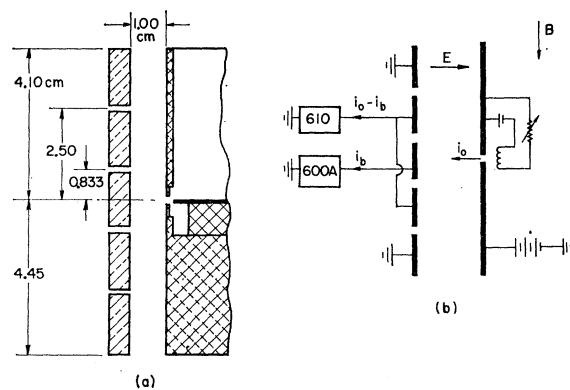

FIG. 5. Experimental details for measuring parallel diffusion. (a) Electrode detail. The three middle anode rings have the same width. The filament is parallel to the slit in the cathode (normal to both the view shown and to B). (b) Electrical schematic for measuring ratio of currents to middle rings. The ratio was $i_b/i_0=0.70$.

most are captured by the cathode. To produce an ob-servable current, the filament current had to be in-creased as B was increased. At very large B, the ob-served current was mostly to the middle ring and therefore could only be from negative ions. This effect was insignificant in hydrogen and deuterium.

To obtain the diffusion coefficients (D_{11}) from the data, we consider one-dimensional diffusion in the parallel (z) direction. Electrons starting from $z=0$ at $t=0$ diffuse into a Gaussian distribution as they drift across the gap.[1] Of the total anode current i, a fraction Δi falls on a strip $2z_0$ wide centered at $z=0$. Integration of the Gaussian distribution of electrons yields $\Delta i/i$ $= \mathrm{erf}(s_0)$, where the argument of the error function is $s_0 = z_0/(4D_{11}t_d)^{\frac{1}{2}}$. The time of interest t_d is the time it takes for electrons to drift across the gap. In the ex-periment, we have $\Delta i/i = 0.70$ and $z_0 = 0.833$ cm, and therefore $D_{11} = 0.33/t_d$; the drift time is found from Eq. (10) with the gap spacing of 1.00 cm. In the range of parameters used, B was only moderately strong, and R_v ranged from 3 to 8.

From Eq. (6) it is seen that the product pD_{11} depends only on the average energy and the cross section. On this basis, we have plotted the measured quantity pD_{11} as a function of E/B. The results are shown in Fig. 6 for hydrogen and deuterium. Except for substantial scatter at the lower energies, the points fall quite well on smooth curves.

6. ANALYSIS OF RESULTS

A. Elastic Cross Section

An iterative process was used to find the elastic cross section and the average energy of the electrons.
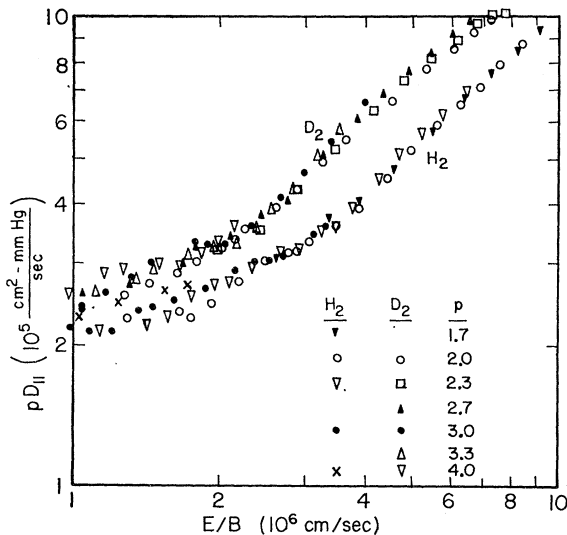

FIG. 6. Product of the pressure and diffusion coefficients as a function of E/B, the perpendicular drift velocity. Data are shown for hydrogen and deuterium at 20°C.
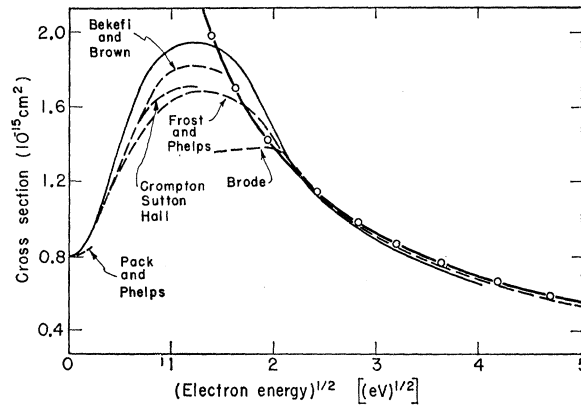

FIG. 7. Elastic (momentum-transfer) cross section for hydro-gen as a function of the electron energy. Present result is shown by a solid line; circled cross section is that for a constant collision frequency.

An assumed cross section taken from published work[12] was used in evaluating the integrals, Eq. (5) and (6), on an IBM 709 computer. The collision frequency ν_c is given in terms of the cross section σ as a function of electron energy by $\nu_c = n_g v \sigma$, where the gas density n_g is taken to be 3.30×10^{16} p/cm^3.[13] These values of the integrals, obtained as a function of the average energy of the electrons, were compared with the experimental values for the drift velocities and diffusion coefficients which were found as a function of E/B. Appropriate changes were made in the cross section until the average energies that corresponded to the same E/B were equal. As the changes were made, the cross section at zero energy was held fixed at the value of Pack and Phelps.[5] Also Brode's values were used for the shape of the cross section at energies above 5 eV.[14]

Using the assumption that the elastic cross section is the same for hydrogen and deuterium, we averaged the results for the two gases to give the cross section shown in Fig. 7. Recent determinations of the cross section by Bekefi and Brown,[15] Frost and Phelps,[12] Crompton and Sutton[16] and Hall[17] are also shown (the values by Crompton and Sutton for H_2 and by Hall for D_2 have been averaged together since the method and apparatus were the same). Also shown for reference is a cross section corresponding to a constant collision frequency. My value reaches a maximum collision fre-quency of almost $6 \times 10^9 p/\mathrm{sec}$ at $T = 20°C$ in the region of 3.0 to 3.5 eV. The cross section shown is somewhat high because of the effect of transverse diffusion, which

[12] L. S. Frost and A. V. Phelps, *Proceedings of the Fifth Inter-national Conference on Ionization Phenomena in Gases* (North-Holland Publishing Company, Amsterdam, 1961).

[13] The letter p here, and in all following quantitative expressions in this paper, denotes the numerical value of the pressure ex-pressed in mm Hg.

[14] R. B. Brode, Revs. Modern Phys. 5, 257 (1933).

[15] G. Bekefi and S. C. Brown, Phys. Rev. 112, 159 (1958).

[16] R. W. Crompton and D. J. Sutton, Proc. Roy. Soc. (London) A215, 467 (1952).

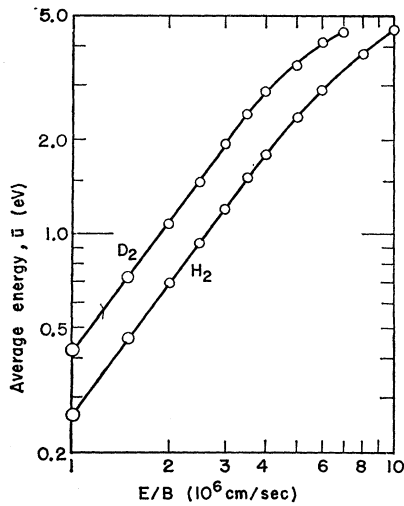[17] B. I. Hall, Australian J. Phys. 8, 468 (1955).

FIG. 8.Average electron energy (in eV) in hydrogen and deuterium as a function of E/B, the perpendicular drift velocity.

made the transverse drift velocity appear larger than it should be. No quantitative adjustment could account for this effect other than the estimate of 5% made earlier in Sec. 4 of this paper. The other possibility for error lies in the assumption of a Maxwellian distribution. In other studies it has been found that different assumed distribution functions made significant differences in the resulting values of cross section and average energy. Calculations show that, in the SMF limit, the transverse drift velocity is much less dependent on the choice of distribution function (such as between Maxwellian and Druyvestyn) than in the case with zero magnetic field.

B. Average Electron Energy

The average energy of the electrons as a function of E/B, shown in Fig. 8, cannot be compared directly with any other work, since there has been no other work in a SMF. (Computer calculations presently being made of the distribution function in a SMF using known values of the elastic, molecular-excitation, dissociation, and electronic-excitation cross sections find average energies agreeing with those measured here.[18] However, comparison can be made by finding the average energy loss parameter η as a function of the average energy, which is plotted in Fig. 9. The fractional energy loss per collision is found by multiplying η by $2m/M$. It can be noted that again much better agreement is found with the results of Bekefi and Brown than with Crompton, Sutton, and Hall. This perhaps suggests that different distribution functions can explain the differences.

By making certain assumptions, comparison of my results can be made with values of the average energy as a function of E/p ($B=0$). For the latter, we use the

[18] Gary A. Pearson, Lawrence Radiation Laboratory, Berkeley, California (private communication).

values given by Brown,[19] which is a composite of values by Townsend and Bailey[7] and by Varnerin and Brown.[20] These two values disagree by about 20% and even further disagreement is found when the values of Crompton and Sutton are considered. Comparison with the present results involves expressing E/p in terms of E/B by means of the equivalent pressure concept, which states that there is an equivalent E/p' with $B=0$ which represents the same average electron energy as E/p with $B>0$.[21] In the SMF limit, one has the equivalent pressure $p'=\omega_b\tau p$. Using this, we can write $E/B=\kappa E/p'$, where $\kappa=\omega_b\tau p/B$. Note that $\kappa/p=e\tau/m$ is the mobility for $B=0$. In effect, if we use the equivalent pressure with $B=0$, the drift velocity along E will equal the perpendicular drift velocity in a SMF.

Since the values of average energy quoted as a function of E/p are for a temperature of 0°C, all collision frequencies used in this paragraph are for that temperature. At this temperature, ν_c has a maximum of 6.5×10^9 p/sec. Figure 10 shows our values of the average energy as a function of E/B compared with several curves obtained from the $B=0$ values using different values of average collision frequency ranging from 3.5 to 6.5×10^9 p/sec.

In the region of 3 to 4 eV, where the collision frequency is a maximum, it is seen that quite good agreement is obtained by using an average collision frequency nearly equal to the maximum. At lower energies, agreement is obtained by using smaller frequencies.
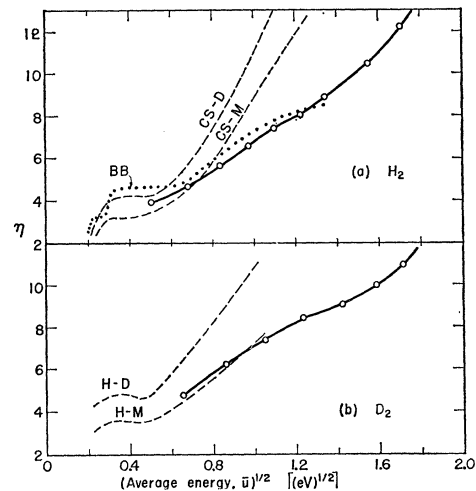

FIG. 9. Average energy loss per collision as a function of the electron energy. The average fractional energy loss per collision is $\lambda=\eta(2m/M)$. (a) Present results for hydrogen are compared with those of Bekefi and Brown (BB) and of Crompton and Sutton (CS) for Maxwell (M) and Druyvestyn (D) distributions. (b) Present results for deuterium are compared with those of Hall (H) for Maxwell (M) and Druyvestyn (D) distributions.

[19] S. C. Brown, Basic Data of Plasma Physics (The Technology Press, Boston, 1959).
[20] L. J. Varnerin, Jr., and S. C. Brown, Phys. Rev. 79, 946 (1950).
[21] H. A. Blevin and S. C. Haydon, Australian J. Phys. 11, 18 (1958).
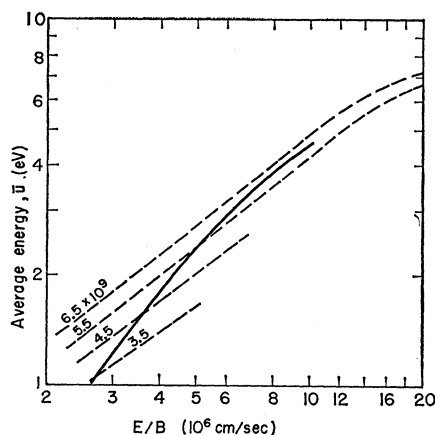
FIG. 10. Average electron energy in H_2 as a function of E/B compared with values measured with $B=0$ as a function of E/p. Latter values are compared at several average collision frequencies, using $E/B = \kappa E/p'$. The collision frequencies of 6.5, 5.5, 4.5 and 3.5×10^9/sec correspond to $\kappa = 2.7, 3.2, 3.9$, and 5.0.

This agrees with the physical situation in which the collision frequency does indeed rapidly decrease for electron energies below 2 eV.

From both Figs. 8 and 9, we can see that the average energy loss per collision in hydrogen is almost twice that in deuterium. Since this energy loss is much larger than that due to elastic collisions (where mass difference accounts for a factor of 2), there must be substantial differences in the energy losses to rotational and vibrational excitation between hydrogen and deuterium, especially in the latter loss. This factor-of-2 difference is observed in comparing the results of Crompton and Sutton and Hall[16,17] and is also observed in the measurements of the first Townsend coefficient at very low E/p by Rose.[22] To our knowledge there is no good calculation of the vibrational-excitation cross section, so there is no explanation for the difference between H_2 and D_2. The results of Frost and Phelps[12] and the recent measurements of Schulz[23] contradict

the theory of Chen and Magee,[24] which gives a very sharply spiked cross section near 7 eV. Using a double electrostatic analyzer, Schulz found that the vibrational cross section in hydrogen reaches a maximum of about 3 to 4×10^{-17} cm^2 at about 3 eV. This agrees well with the value of Frost and Phelps.

The effect of the vibrational excitation can apparently be observed in the drift-velocity data for hydrogen (Figs. 3 and 4) as a small dip near $E/B = 3 \times 10^6$ cm/sec. Any such dip in deuterium was not observable.

CONCLUSION

It is shown that in the SMF limit, the average energy of the electrons is a function of E/B as predicted by theory. Values of the transverse drift velocity across a magnetic field are found and are perhaps a little large because of transverse diffusion. A direct measurement of the transverse drift velocity by other means (such as light-pulse techniques, which should give good accuracy in a strong magnetic field) is needed to confirm the velocity-ratio measurements reported here. A value is found for the elastic-collision cross section in hydrogen which is somewhat higher than reported by other authors. Values of the average energy of electrons in hydrogen and deuterium are found to agree reasonably well with other work when compared in a suitable manner. Theoretical work is needed to explain why the average inelastic-collision energy loss per elastic collision in hydrogen is about twice that in deuterium.

[22] D. J. Rose, Phys. Rev. 104, 273 (1956).
[23] G. J. Schulz, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania (private communication).

[24] J. C. Y. Chen and J. L. Magee, J. Chem. Phys. 36, 1407 (1962).