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Drift Velocity of Electrons in Nitrogen, Helium, Neon, Argon, Krypton, and Xenon*

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Accurate values of electron drift-velocity in purified noble gases and nitrogen have been obtained by measuring the transit time of photoelectrons across the gap of a parallel-plate condenser. Drift velocities in pure krypton and xenon have not been measured before. The values obtained for the other gases are invariably lower than those reported by Nielsen, the discrepancy for neon being large. The sharp maximum found by English and Hanna for argon at $E/p_0<0.1$ and tentatively ascribed by them to the Ramsauer effect was not observed in the purified gas.

INTRODUCTION

ACCURATE data on the drift velocity $\bar{\omega}$ of electrons in gases are of value not only in the design of gas-filled radiation-detection devices and in the study of gas-discharge phenomena, but also as a source of information concerning electron collision cross sections in the low-energy region. Nielsen's[1] measurements of $\bar{\omega}$ in nitrogen, helium, neon, and argon are generally regarded as the most reliable for these gases. The present inquiry was undertaken initially to study $\bar{\omega}$ in gas mixtures. However, since results obtained in the purified gases were found to be consistently lower than Nielsen's values, they are reported at this time together with the data for krypton and xenon. Possible reasons for the discrepancies are discussed and evidence indicating that Nielsen's values are too large is given. In a separate paper[2] the experimental data are analyzed to obtain information about the transport cross section below about 10 ev.

APPARATUS

The experimental arrangement, outlined in Fig. 1, is similar to that used by Hornbeck.[3] A light pulse of $\sim$0.4 μsec half-width duration from flash tube A passes through quartz window B and perforated anode C, striking cathode D and releasing a group of photoelectrons which then drift under the action of a uniform field and induce a current in an external resistor. The signal is amplified by a Tektronix 121 preamplifier which has a 12-Mc/sec bandwidth and is coupled to a Tektronix 517 oscilloscope. A single-trace transient is displayed on the oscilloscope each time the flash tube fires. Typical examples of the oscillograms, which were recorded on 35 mm film, are shown in Fig. 2, from which the time resolution of the method can be judged.

Since it is generally believed that $\bar{\omega}$ in the noble gases is extremely sensitive to gaseous impurities, great care was exercised in the design and construction of the chamber and gas-handling system. The use of mercury manometers, vacuum greases, composition gaskets, and organic substances likely to evolve gases was avoided. Shutoff valves to the chamber were of the all-metal type. A vacuum-tight quartz window $1\frac{3}{8}$ inches in diameter by 1 mm thickness was attached to the chamber by first soldering[4] it to a copper-expansion ring which was then used as the sealing gasket. Electrical glass-kovar feedthroughs and Swagelok fittings were mounted on the chamber by screwing them into threaded holes equipped with ferrules, thereby eliminating the necessity of soldering. Gas pressure was

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] R. A. Nielsen, Phys. Rev. **50**, 950 (1936).
[2] J. C. Bowe, following paper [Phys. Rev. **117**, 1416 (1960)].
[3] J. A. Hornbeck, Phys. Rev. **83**, 375 (1951).
[4] The periphery of the window was treated with Hanovia preparation No. 130-A, which allowed it to be tinned and soft-soldered.

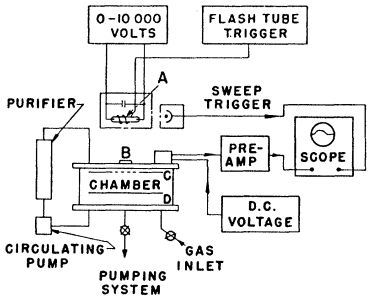

FIG. 1. Schematic diagram of the experimental arrangement. *A* is a quartz flash tube, *B* a quartz window, *C* a perforated anode, and *D* a photosensitive cathode.

measured with a Wallace and Tiernan precision dial manometer of all-metal construction.

Parallel plates, $7\frac{1}{2}$ inches in diameter and accurately separated by 1 inch, were mounted and supported with standoffs made of Kel-F. The cathode was a disk of flat pyrex plate-glass, coated with tin to provide a photosensitive surface. A lead gasket sealed the chamber, and the entire system was tight when tested with a helium leak-detector operated at maximum sensitivity.

METHOD

A vacuum of 2×10^{-6} mm Hg, as indicated by an ionization gauge, was attained with a diffusion pump and liquid-nitrogen cold trap. At this pressure, the chamber was baked at 80°C for a few days while the calcium turnings in the purifier were outgassed at 500°C. Before filling, the chamber was flushed and evacuated a few times with the gas under study, thereby diluting the residual gas molecules to negligible proportion. Purification was achieved by forced circulation of the gas over hot calcium turnings prior to and during the course of measurements. Preliminary drift-velocity data were usually recorded immediately upon filling the chamber in order to compare with results obtained after the gas had been circulated.

The duration of the current pulse, measured between the midpoints of the leading and trailing edge (Fig. 2), is interpreted as a direct measure of the electron transit-time from cathode to anode. This measurement is made with an accuracy corresponding to ±1 mm referred to the oscilloscope. Since the pulse-width can always be confined to a value between 40 mm and 80 mm, the corresponding maximum error in transit time is 2.5%. The limits of error associated with each time measurement are indicated in the figures by short vertical lines. Other possible sources of error, such as calibration of sweep speed, variation of battery voltages, and measurement of gas pressure, lead to a conservative estimate of 5% for the over-all error. The reproducibility of the data is well within this limit. The electric-field distortion due to space charge is estimated to be 1% with 80 volts on the chamber. Field distortion was greater than 1% for values of E/p_0 to the left of the line drawn perpendicular to the abscissa on Figs. 3, 4, 5, 7, and 8. Measurements were terminated for each gas at the E/p_0 value where electrical breakdown became evident.

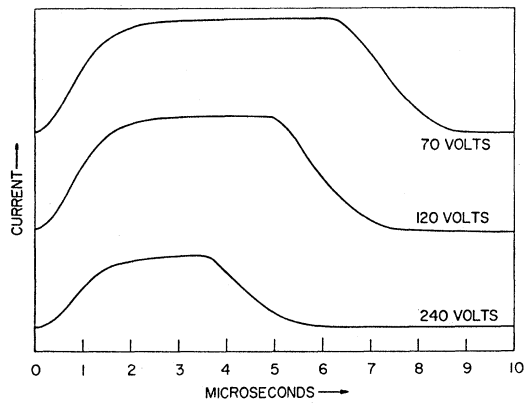

FIG. 2. Examples of typical current pulses obtained in helium at $p_0=112$ mm Hg. The increase of drift velocity with chamber voltage and the time resolution of the method are illustrated.

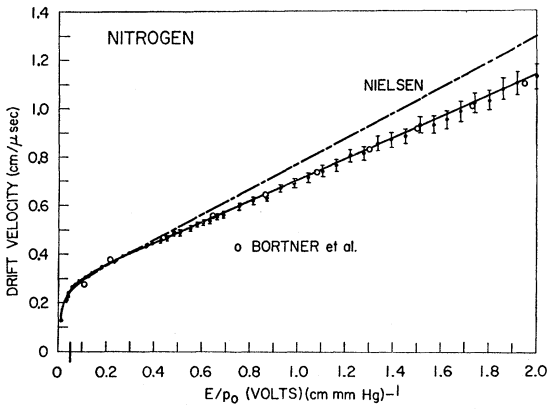

FIG. 3. Drift velocity of electrons measured at $p_0=653$ mm Hg. Comparison is made with measurements of Nielsen[1] and of Bortner *et al.*[5] All data in this figure and subsequent figures are normalized to 0°C. Space-charge distortion of the electric field is estimated to be greater than 1% for values of E/p_0 smaller than that indicated by the vertical line in this and subsequent figures.

RESULTS

Nitrogen

Tank nitrogen, obtained from Matheson Company and having a stated purity of 99.996%, was used. Oxygen and hydrogen were given as the major impurities. The calcium purifier was operated at 350°C.

The results obtained are shown in Fig. 3, where comparison is made with the data of Nielsen[1] and of Bortner *et al.*,[5] both normalized to 0°C. Since excellent agreement was obtained with the results of the entirely different method used by Bortner *et al.*, it is concluded that the curve for nitrogen is known to an accuracy of 3% up to $E/p_0=2$.[6]

[5] Bortner, Hurst, and Stone, Rev. Sci. Instr. 28, 103 (1957).
[6] p_0 is the pressure normalized to 0°C.

Helium

Tank helium of research grade, obtained from Matheson Company, was used. Nitrogen, in the amount of less than 0.01%, was given as the major impurity. A drift-velocity curve, determined immediately after the gas was admitted to the chamber, was identical to subsequent curves taken after the gas had been circulated over the calcium turnings at 450°C. That gases evolved from the metal chamber did not affect $\bar{\omega}$ was demonstrated by the fact that identical results, within experimental error, were obtained after the helium had been stored in the chamber for five months, without further purification. There is substantial experimental agreement for helium up to $E/p_0=2.0$, in which region the values of Townsend and Bailey,[7] Nielsen,[1] Hornbeck,[8] and Errett[8] are all within about 10% of each other. The results suggest that $\bar{\omega}$ is not extremely sensitive to gas impurities at concentrations of order of magnitude of 0.01%, and that achievement and maintenance of sufficient purity for the measurements is not a major problem. However, the effects of gas additives in helium merit further study. The present results are compared with those of Nielsen in Fig. 4.

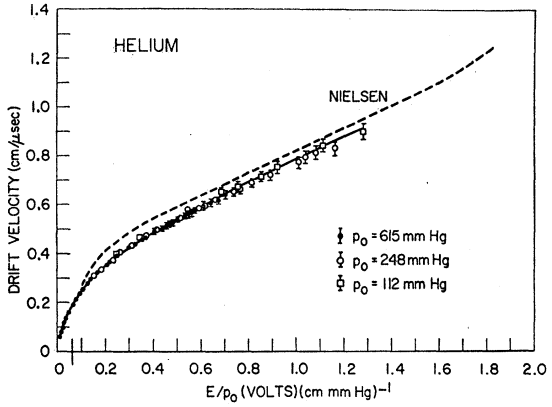

FIG. 4. Drift velocity of electrons measured at indicated pressures. Comparison is made with Nielsen's[1] measurements.

Neon

Reagent-grade tank neon, obtained from Matheson Company, was used. Helium and nitrogen, in the amounts of less than 0.03% and 0.01%, respectively, are given as the major impurities. The calcium purifier was operated at 450°C. Results obtained prior to circulation, however, were identical within the experimental error.

The present measurements are shown in Fig. 5, where comparison is made with the experimental results of Nielsen. The large discrepancy in the shape of the curve is thought to be due to a difference in gas purity. It is commonly observed that lower values of $\bar{\omega}$ are obtained in a gas of higher purity.

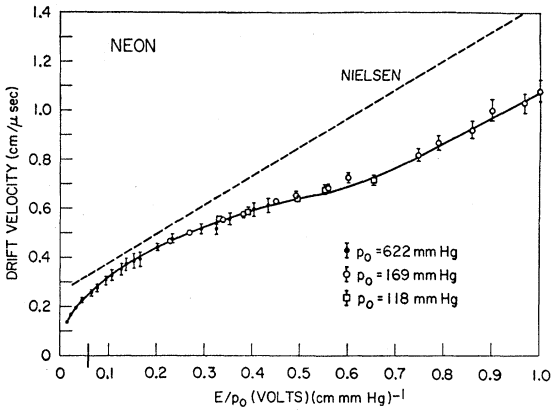

FIG. 5. Drift velocity of electrons measured at indicated pressures. Comparison is made with Nielsen's[1] measurements.

Argon

Tank argon, obtained from Cleveland Wire Works and having a stated purity of 99.99%, was used. A typical analysis furnished by the manufacturer gave the following impurities: hydrogen, none; water vapor, less than 3 ppm; oxygen and carbonaceous gases, each less than 5 ppm; and nitrogen, less than 10 ppm. The results obtained immediately after filling the chamber are presented in Fig. 6, where the sensitivity to these impurities and the effectiveness of the hot calcium purifier are illustrated. English and Hanna[9] were the first to report the sharp maximum[10] at $E/p_0=0.01$, and they conjectured that it was due to the Ramsauer

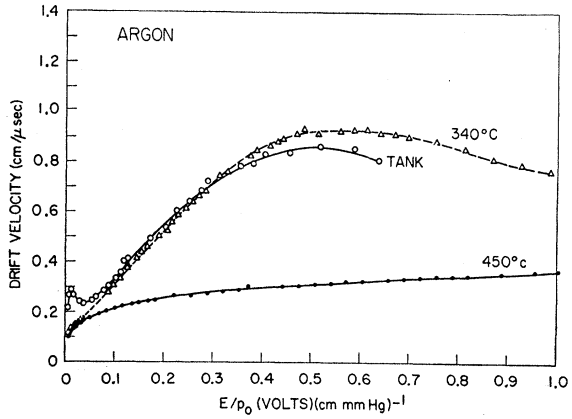

FIG. 6. Drift velocity of electrons measured at $p_0=680$ mm Hg. Circled points represent measurements taken immediately after filling the chamber. Points enclosed in triangles were obtained with the purifier operated at 340°C and the lower curve with the purifier at 450°C.

[7] J. S. Townsend and V. A. Bailey, Phil. Mag. **46**, 657 (1923).
[8] D. D. Errett, Ph.D. thesis, 1951, Purdue University (unpublished).
[9] W. N. English and G. C. Hanna, Can. J. Phys. **31**, 768 (1953).
[10] Errett[8] observed this effect earlier in A-CO_2 and A-water vapor mixtures.

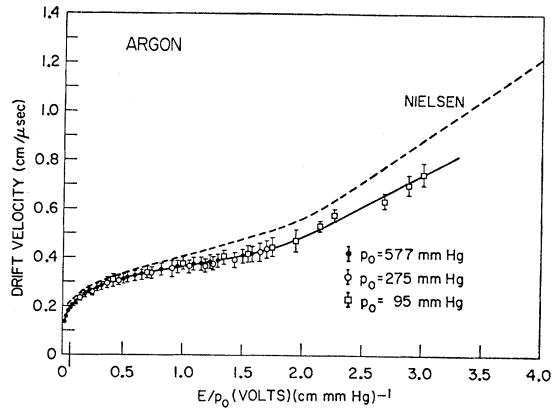

FIG. 7. Drift velocity of electrons measured at indicated pressures. Comparison is made with Nielsen's[1] measurements.

maximum in the mean free path at very low energy in the pure gas. Measurements in the purified gas, however, give no indication of the "resonance." The data in Fig. 6 indicate that this maximum was made manifest by some contaminant gas which was removed by calcium at 340°C. At the higher temperature of 450°C, the contaminant responsible for the broad maximum was also removed. Prolonged circulation produced no further change in $\bar{\omega}$, indicating that sufficient purity had been obtained. The effectiveness of the care exercised to keep the gas clean was illustrated by repeating the argon measurements after the gas had been stored in the chamber for 8 weeks. Without further purification, the drift-velocity curve was identical within the experimental error.

In Fig. 7, the present results are compared with Nielsen's experimental curve normalized to 0°C. The measurements of Bortner *et al.*[5] yielded a curve which was somewhat higher than both of these. Errett's[8] values are in agreement with the author's up to $E/p_0 = 1.6$; at $E/p_0 = 3.2$ his value is 7.5% higher. It is well known that the upturn in the $\bar{\omega}$ curve, which occurs in the present data at about $E/p_0 = 1.6$, is due to inelastic collisions exciting the first excited state. The fact that

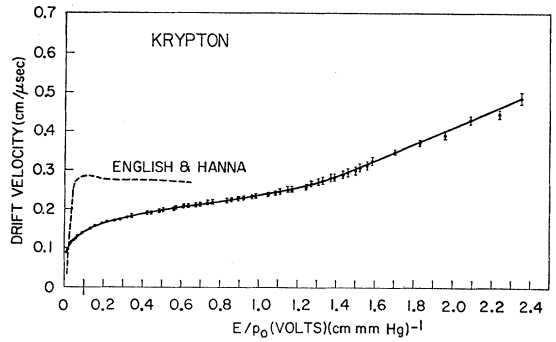

FIG. 8. Drift velocity of electrons measured at $p_0 = 302$ mm Hg. Comparison is made with measurements (dashed curve) of English and Hanna.[9]

this occurs at a lower E/p_0 than in Nielsen's curve is indicative of greater gas purity.

Krypton and Xenon

The gases used were reagent grade obtained from Matheson Company. Prior to filling the chamber, each gas was transferred to a pyrex flask containing activated charcoal in a freeze-out thimble at liquid-nitrogen temperature. Drift-velocity curves determined prior to circulation through the calcium cell were identical to results obtained with the purifier operated at 450°C. English and Hanna[9] obtained results with unpurified krypton and xenon which lie higher; these are also presented in Figs. 8 and 9.

DISCUSSION

The discrepancies with Nielsen's data do not seem to have their origin in gross differences in gas purity,

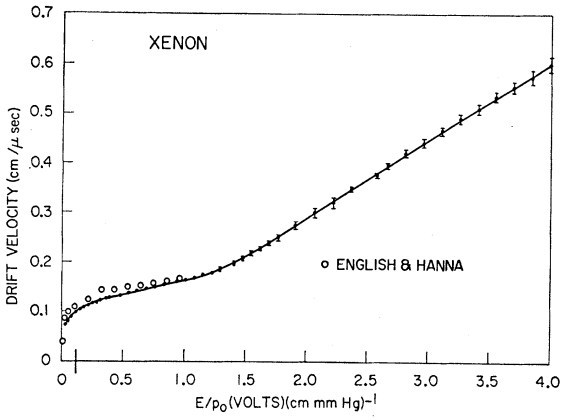

FIG. 9. Drift velocity of electrons measured at $p_0 = 267$ mm Hg. Comparison is made with measurements (open circles) of English and Hanna.[9]

with the possible exception of neon. Past experience reported in the literature has shown that molecular impurities markedly increase the drift velocity and substantially alter the shape of the curve. The discrepancies reported here are thought to be due either to Nielsen's failure to correct for diffusion or to some instrumental error in either apparatus. Duncan[11] has shown that the diffusion correction in an electron-shutter apparatus such as was used by Nielsen would reduce the $\bar{\omega}$ values. Other experimental evidence which indicates that Nielsen's $\bar{\omega}$ values are too high is found in the measurements, made by a different method, of Errett.[8] The measurements of Bortner *et al.* in nitrogen are also lower than Nielsen's.

In the present experiments, the width of the current pulse at half-maximum corresponds to the average time

[11] R. A. Duncan, Australian J. Phys. **10**, 54 (1957); see also Crompton, Hall, and Macklin, *ibid.* **10**, 366 (1957).

required by the electrons to cross the parallel-plate gap. The midpoints of the leading and trailing edges represent the time coordinates when half the total number of electrons leave the cathode and arrive at the anode, respectively. With this interpretation, the time measurements could possibly be in error for any of the following reasons: (1) the photoelectrons are not released with an energy distribution characteristic of the impressed electric field, (2) diffusion of the electron cloud shifts the relative position of the median plane, and (3) the signal waveform is distorted by the input circuit. The error introduced by the first of these can be neglected if equilibrium with the electric field is established in a distance which is small compared with the total drift distance. If it is assumed that equilibrium is established in a fixed number of collisions, an empirical test for this correction can be made by changing the gas pressure. Reproducibility of the drift-velocity curves under various pressures, as shown in the figures, implies that no correction need be made over the pressure range used for these measurements. Diffusion would introduce no error if the electron swarm expanded symmetrically about its median plane perpendicular to the electric field. If the expansion were asymmetric, a net diffusion current would flow parallel to the field thereby introducing a relative displacement of the median plane and consequently, a change in the drift-time. The magnitude of the error due to this effect is expected to be larger at lower pressure, but since no pressure effect was observed, the correction is judged to be negligible. Distortion of the waveform by the input circuit was tested at various times by decreasing the time constant by a factor of ten. The drift time measured under this condition was in agreement with previous measurements; hence, no correction for this effect is made.

It is noteworthy that in the cases tested, storage of the purified gas in the metal chamber had no effect on the drift velocity. This may mean either that $\bar{\omega}$ is insensitive to the particular gases released by the chamber walls, or that these gases are released at such a low rate as to be ineffective. Since the effects of gaseous impurities are not completely known, the answer must await future measurements in purified gases diluted with small known quantities of trace gases. It is not improbable that in helium and neon, $\bar{\omega}$ is not as sensitive to gas additives as has occasionally been supposed.

The limits of purity reached by the techniques described above cannot be assessed. However, the effectiveness of the calcium turnings was strikingly demonstrated in the case of argon and the results enabled identification of an artifact which was not previously known to be due to impurities. Moreover, because of the well-known inverse relation between $\bar{\omega}$ and the electron agitational energy $\bar{\epsilon}$, removal of molecular impurities tends to increase $\bar{\epsilon}$ and therefore decrease $\bar{\omega}$. Since the present measurements do not lie above any of the previously existing determinations and lie substantially below them for neon, the above facts may be taken as evidence of gas purity. The results presented here probably represent the cleanest gas measurements presently available.

ACKNOWLEDGMENT

The writer expresses his appreciation to F. F. Rieke of Chicago Midway Laboratories for an interesting discussion concerning the analysis of the experimental data. The guidance of L. D. Marinelli in the preparation of this paper is gratefully acknowledged.