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INVESTIGATION OF CHARGE DIFFUSION IN IONIZED GASES BY THE DIFFUSION-WAVE TECHNIQUE

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The diffusion-wave technique has been used to measure the diffusion coefficients for charged particles in low-density ionized gases (H_2, He, Ne, Ar, Kr, and Xe). At pressures of 0.03–1 mm Hg, magnetic fields up to 1500 Oe, ion densities of 10^8–10^{10} cm^{-3}, and an electron temperature of approximately 1 eV, the dependence of the transverse diffusion coefficient on magnetic field corresponds, in most cases, to that predicted on the basis of binary collisions between charged particles and neutrals.

1. INTRODUCTION

In earlier papers[1,2] we have described the theory and experimental application of the diffusion-wave technique in the investigation of the longitudinal ($D_{\parallel}$) and transverse ($D_{\perp}$) coefficients of ambipolar charge diffusion in an ionized gas in a magnetic field. In the present work we report on results obtained using this technique to measure $D_{\parallel}$ and $D_{\perp}$ in the gases H_2, He, Ne, Ar, Kr, and Xe (the preliminary results of the measurements in He and Ar[2] are replaced by more accurate later results). The measurements were performed with an apparatus (Fig. 1) that has been described in detail in [2]. A thermionic arc is produced in a glass tube 2; the plasma diffuses through an aperture 3 into the glass tube 4 located in a solenoid 6. The power supply 1 provides the voltage for tube 2; this voltage is modulated at an audio frequency causing the density of charged particles in this tube to vary sinusoidally about some mean value. The diffusion density waves, which propagate in tube 4, are detected by the movable double probe 5 and the oscilloscope 7.

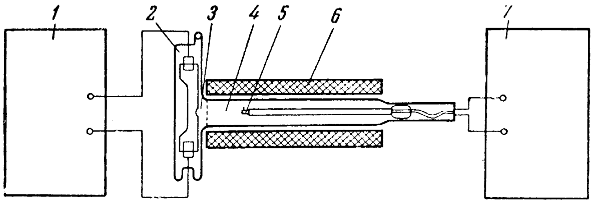

FIG. 1. Experimental apparatus (cf. [2]).

The measurement of the amplitude attenuation factor of the density waves δ at high modulation frequencies and high magnetic fields H can be used to find $D_{\parallel}$:

$$\delta = \sqrt{\omega / 2D_{\parallel}}, \tag{1}$$

where ω is the angular modulation frequency.[2] The ratio $D_{\parallel}/D_{\perp}$ is found by operating at low modulation frequencies:

$$\sqrt{D_{\parallel} / D_{\perp}} = \delta(0) / \delta(H). \tag{2}$$

2. EXPERIMENTAL RESULTS

The experiments were carried out in spectrally pure inert gases and in hydrogen (the vapors of the stopcock grease were frozen out by liquid nitrogen, except for the experiment with Xe) at residual tube gas pressures of 10^{-6} mm Hg. The hydrogen was obtained electrolytically and subject to subsequent purification by copper filings heated to 300°C.

The measurements were carried out at gas pressures of 0.03—1 mm Hg, at electron densities $n_e = 10^8 - 10^{10}$ cm^{-3}, magnetic fields up to 1500 Oe, and modulation frequencies ranging from 40 to 10^4 cps. The electron temperature T_e was measured with a double probe with no field, and with $H \sim 10^3$ Oe; the quantities T_e and n_e with H = 0 were also measured with a Langmuir probe. The electron temperature T_e in tube 4 exhibited essentially no change over the entire measured distance (0—15 cm) from the input aperture 3 (Fig. 1). Typical measurements of T_e in Kr are shown in Fig. 2. The mean values of T_e for all gases (with and without magnetic field) are shown in Table I.

The curves in Fig. 3 show the attenuation of the diffusion waves in Xe and the reduction in electron density n_e with no magnetic field. The slope of these curves is determined by the attenuation coefficient δ. Values of δ measured at a modulation frequency of 40 cps are used to compute the ratio $D_{\|}/D_{\perp}$; typical results are shown in Fig. 4. Within ±20% the slope of the line $\log(D_{\|}/D_{\perp} - 1) = f \log(H)$ is approximately 2 (with the exception of Kr at p = 0.03 mm Hg) so that we can write

$$D_{\|}/D_{\perp} = 1 + \alpha H^2 = 1 + \alpha_1 (H/p)^2. \quad (3)$$

The results of the determination of α are shown in Table I. In this table we also show the results of measurements of $D_{\|}$; modulation frequencies of $10^3 - 10^4$ cps were used in these measurements.

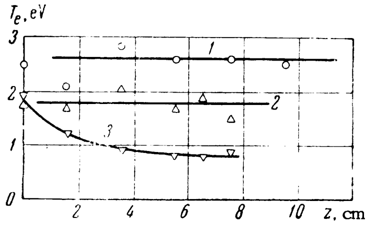

FIG. 2. Electron temperature at various distances from the input aperture (in Kr): 1) p = 0.03 mm Hg, H = 1100 Oe; 2) p = 0.1 mm Hg, H = 1100 Oe; 3) p = 0.1 mm Hg, H = 0.

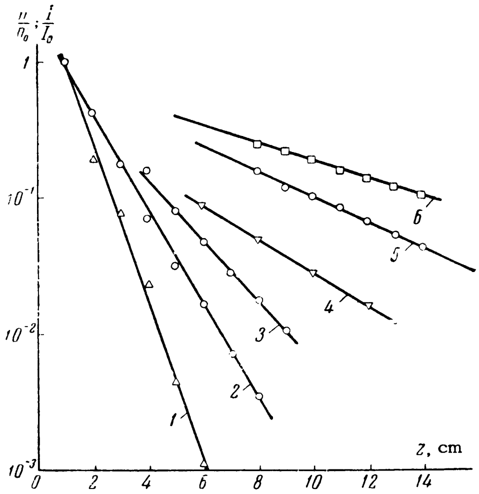

FIG. 3. Amplitude of diffusion waves (f = 40 cps) in Xe at p = 0.1 mm Hg: curve $1 - n_e(z)/n_e(0)$ [$n_e(0) = 2.7 \times 10^{10}$ cm^{-3}, H = 0]; curves 2, 3, 4, 5 and 6 give the wave amplitude for H = 0, 140, 290, 860 and 1440 Oe.

3. DISCUSSION

1. We have noted earlier[1] that reliable measurements of damping can only be obtained at dis-

Table I

Gas	p, mm Hg	T_e, eV ($H=0$)	T_e, eV ($H \sim 10^3$Oe)	α, Oe^{-2}	$D_{\|}$, cm^2/sec
H_2	0,03	—	1.1	$2.3\cdot10^{-3}$	—
	0.1	0.9	1.5	$1,1\cdot10^{-4}$	—
	1.0	0.6	0.7	—	$1.2\cdot10^{4}$
He	0,1	2,1	2,8	$1.4\cdot10^{-4}$	—
	0.3	2.2	2.5	$1,7\cdot10^{-5}$	—
	1.0	1.0	2.8	$1,9\cdot10^{-6}$	$6,3\cdot10^{4}$
Ne	0.1	1.8	3.2	$2.2\cdot10^{-4}$	$1.5\cdot10^{5}$
	0.3	1.5	2.3	$3.2\cdot10^{-5}$	$7.5\cdot10^{4}$
	1,0	1.1	1,2	$8.0\cdot10^{-6}$	$1.6\cdot10^{4}$
Ar	0.03	1.6	2.2	$4.0\cdot10^{-4}$	$1.5\cdot10^{5}$
	0.1	1.3	1.5	$3,0\cdot10^{-5}$	$3.5\cdot10^{4}$
	0.3	1.1	1.1	$1.1\cdot10^{-5}$	$9,3\cdot10^{3}$
Kr	0,03	—	2.6	—	$1.4\cdot10^{5}$
	0.1	—	1.8	$4,0\cdot10^{-5}$	$3.9\cdot10^{4}$
	0.3	0.9	1.0	$1,1\cdot10^{-5}$	—
	1.0	—	0.6	$1,4\cdot10^{-6}$	—
Xe	0,03	—	1.6	$1.6\cdot10^{-4}$	$1.4\cdot10^{5}$
	0.1	0.85	1.0	$2.2\cdot10^{-5}$	$3.5\cdot10^{4}$
	0.3	—	0,7	$1,8\cdot10^{-6}$	$0.85\cdot10^{4}$

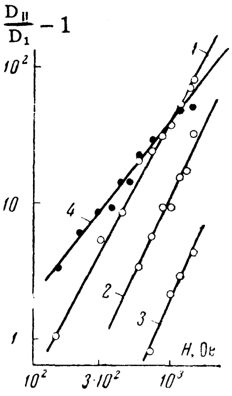

FIG. 4. Effect of magnetic field on diffusion coefficient (Kr): 1) p = 0.1 mm Hg; 2) p = 0.3 mm Hg; 3) p = 1.0 mm Hg; 4) p = 0.03 mm Hg.

tances far enough from the entrance aperture so that a normal diffusion distribution of charged particles over the tube cross section n(r) can be established. Using the formulas given in [1] we write the relation

$$n(\zeta) = n\{(z/R)\sqrt{D_\perp/D_\parallel}\}$$

(R is the tube radius) in the form

$$n(\zeta) = \sum_{k=1}^{\infty} C_k \exp(-x_k\zeta) \approx \sum_{k=1}^{4} C_k \exp(-x_k\zeta), \quad (4)$$

where x_k is the k-th root of the Bessel function $J_0(x)$. Using this relation we compare the experimentally determined function n(z) with the theoretical relation (Fig. 5). It is evident from this figure that n(z) corresponds to the normal diffusion distribution $n(r) = n_0 J_0(2.4r/R)$ at distances of 1—2R from the end of the tube (R = 1.8 cm in this work) since $n(\zeta) \approx \exp(-2.4\zeta)$. The probe can be moved to a distance z = 8R from the end of the tube so that values $D_\parallel/D_\perp \sim 10^2$ can be measured.

2. As in [2], in certain gases we determine experimentally the dependence of ion probe current I_p on ion density $n_p = n$:

$$I_p \approx n^\beta, \quad (5)$$

where $\beta \sim 0.6$—0.7. The quantity β can be determined by measuring $n_e(z)$ with a Langmuir probe with H = 0 while $I_p(z)$ is measured with a double probe (or by measuring the diffusion-wave attenuation at low modulation frequencies [2]). A typical example is shown in Fig. 3 (curves 1 and 2). The quantity β can also be calculated. [5]

The functional form in (5) was used to compute the theoretical curves in Fig. 5 and to compute $D_\parallel$ from the attenuation measurements at high modulation frequencies ω. The value of δ_∞ [(1)] was computed from

$$\delta_\infty = \delta_e + [(1-\beta)/\beta]\,\delta_I(H), \quad (6)$$

where δ_e is the experimental value of the attenuation coefficient and $\delta_I(H)$ is the attenuation of the ion current at the magnetic field used in measuring δ_e. Equation (6) is derived from (5) making use of the fact that the attenuation of the diffusion wave at high modulation frequencies is different from the attenuation of the ion density in the same magnetic field.

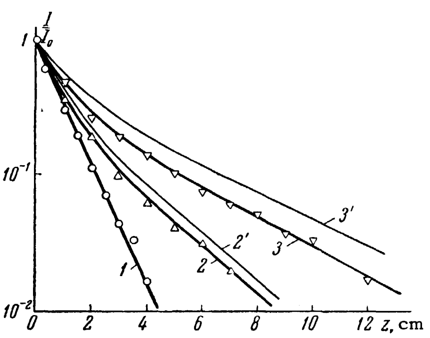

FIG. 5. Comparison of the experimentally found damping of diffusion waves in Kr (p = 0.1 mm Hg) with the damping calculated from Eq. (4): 1) H = 0 (experiment), 2) H = 290 Oe (experiment), 2′) = 290 Oe (calculated), 3) H = 580 Oe (experiment), 3′) H = 580 Oe (calculated).

3. The small drop in electron temperature T_e [1)] at distances as great as 10 cm from the input aperture cannot be reconciled with electron energy balance considerations even if one takes account of elastic and inelastic collisions or collisions of the second kind with metastables. The observed experimental dependence $T_e(z)$ can be attributed to "heating" of the electron gas by the fluctuating electric fields associated with nonthermal noises in the gas discharge tube; these noise fields are propagated in the plasma along with the diffusion waves. The potential fluctuations between the leads of the double probe in the plasma were measured with a sensitive amplifier and an oscilloscope.

The measurements were performed in He and Ar with H = 0 at pressures of 0.03—0.1 mm Hg. The frequency of these fluctuations is 10^5—10^6 cps and the amplitude is 10^{-2}—10^{-1} V, corresponding to a fluctuating electric field of 10^{-2}—10^{-1} V/cm. The value of T_e can be estimated from these data: [6] $T_e \sim 1$—10 eV; this value is of the same order of magnitude as the measured value of T_e. It is evident from Table I that T_e is higher in the magnetic field; it is also found that the noise amplitude

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[1)] Strictly speaking the value of T_e measured here is the mean electron energy (order of magnitude). The electron distribution function in the plasma in tube 4 (Fig. 1) is deficient in fast electrons since there is no volume ionization by electron impact. At low energies the distribution function is approximately Maxwellian: the voltage-current characteristics of the Langmuir probe (H = 0) are straight (except for Ne).

Table II

Gas	p, mm Hg	T_e, eV ($H \sim 10^3$)	$10^{-3} D_{\parallel} p$	$10^6 \alpha_1$	Q_{e1}	Q_{e1} from [5]	$10^{-3} b_{p1}$	$10^{-3} b_{p1}$ from [5]
H_2	0.03	1.1	—	2,1	22	48	17	11,2
	0.1	1.5	—	1.1	33	48		(10)
	1.0	0.7	12	—	—	—		
He	0.1	2.8	—	1.4	25	18	23	10
	0.3	2.5	—	1.5	25	20		(20)
	1.0	2.8	63	1.9	18	18		
Ne	0.1	3.2	15	2.2	6	7.5	9	4
	0,3	2.3	23	2.9	5	6.5		(6.6)
	1.0	1.2	16	8	3	5		
Ar	0.03	2.2	4.5	0.36	11	12	2.3	1,6
	0.1	1.5	3.5	0.3	16	9		
	0.3	1.1	2.8	1.0	6	5		(2.6)
Kr	0.03	2.6	4.2	—	—	—	1.9	0.9
	0.1	1.8	3.9	0.4	9	15		
	0.3	1.0	—	1.1	5	4		(1.2)
	1.0	0.6	—	1.4	4.5	4		
Xe	0.03	1.6	4,2	0.15	(43)	25	(3.2)	0.6
	0.1	1.0	3.5	0.22	(38)	8		(0.8)
	0.3	0,7	2.5	0.16	(63)	5		

increases when the magnetic field is applied. This result was verified experimentally with a noise measuring device (noise frequency 10^5—10^6 cps). A final resolution of the origin of the dependence of $T_e(z)$ will require special experiments.

Fluctuating electric fields in arbitrary directions at frequencies of 10^5—10^6 cps can cause anomalous transverse diffusion in a magnetic field.[3] An estimate shows that under the present conditions the anomalous diffusion becomes stronger than the classical diffusion when H/p > 10^4—10^5 Oe mm Hg; the present measurements, however, were carried out at $H/p < 10^4$. As indicated above, the functional dependence $D_{\perp}(H)$ in the present experiments is approximately classical: $D_{\parallel}/D_{\perp} - 1 \sim H^2$. The only exception found in the present work is for Kr at a pressure of 0.03 mm Hg (Fig. 4, curve 4). Evidently anomalous diffusion comes into play at smaller values of H/p in this case.

4. The diffusion coefficients are determined to an accuracy of approximately 50% in these experiments. Using the values of T_e measured under the same conditions we can estimate the ion mobility b_{p1} and the probability of collisions between electrons and atoms Q_{e1}. The mobility b_{p1} is determined from the diffusion coefficient $D_{\parallel}$:

$$D_{\parallel} p = b_{p1} T_e.$$

The probability Q_{e1} is determined from the relation

$$\alpha_1 = \omega_e \tau_e \omega_p \tau_p (p/H)^2 = 2{,}6 \cdot 10^{-9}\, b_{p1}/Q_{e1}(T_e)\sqrt{T_e},$$

where ω_e and ω_p are the gyromagnetic frequencies of the electrons and ions, τ_e and τ_p are the electron-atom collision time and the ion-atom collision time, α_1 is given in units of (mm Hg/Oe)^2, Q_{e1} in units of cm^{-1}(mm Hg)$^{-1}$, T_e in Ev and b_{p1} in cm^2 V^{-1} sec^{-1} mm Hg. Estimates of b_{p1} and Q_{e1} are given in Table II and compared with the data available in the literature.[4] (Our results for Xe are least reliable because of possible impurities.)

In conclusion I wish to thank V. A. Granovskiĭ for proposing this topic and the experimental technique as well as for guidance and valuable comments.

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