SOVIET PHYSICS

JETP

A translation of the Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki.

Vol. 18, No. 3, pp. 883-1158 (Russ. Orig. Vol. 45, No. 5, pp. 1285-1690, November 1963) April 1964

INVESTIGATION OF TRANSVERSE (HALL) DIFFUSION IN A PLASMA OF INERT GASES

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Submitted to JETP editor January 24, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **45**, 1285-1293 (November, 1963)

Transverse diffusion of ions and electrons in a positive column in a homogeneous longitudinal magnetic field is investigated. The velocities and the Hall diffusion coefficients of charged particles in helium, neon, and argon are determined by probe techniques as functions of the magnetic field intensity, the current through the plasma, the neutral gas pressure and the nature of the gas. A comparison of the experimental data with the theory indicates that the measured values are in accord with the diffusion theory involving pair collisions with neutral molecules.

1. INTRODUCTION

A decrease in the concentration of charged carriers takes place in a long plasma column, bounded by a circular cylindrical tube, and their diffusion occurs in the radial direction. Upon application of a homogeneous magnetic field parallel to the z axis, a transverse (Hall) component of the diffusion is also generated, [1] which has an azimuthal direction, and whose velocities in a partially ionized plasma are expressed as follows: [2]

$$v_{e\varphi} - v_{g\varphi} = -\omega_e\tau_e^2 \frac{e}{m_e}\left(-E_r + \frac{kT_e}{e}\frac{d}{dr}\ln n\right)/(1+\omega_e^2\tau_e^2), \quad (1)$$

$$v_{p\varphi} - v_{g\varphi} = \omega_p\tau_p^2 \frac{e}{m_p}\left(E_r + \frac{kT_e}{e}\frac{d}{dr}\ln n\right)/(1+\omega_p^2\tau_p^2). \quad (2)$$

Here $v_{e\varphi}$, $v_{p\varphi}$, $v_{g\varphi}$ are the velocities of electrons, ions, and atoms of the neutral gas in the azimuthal direction, referred to the laboratory system of coordinates; ω_e, ω_p are the gyromagnetic frequencies of the electrons and ions; τ_e, τ_p are the mean times between collisions of electrons and ions with atoms of the neutral gas; E_r is the intensity of the electric field in the radial direction; $d\ln n/dr$ is the relative concentration gradient of charged particles in the radial direction.

In the case of bipolar diffusion in a plasma ($\lambda_e, \lambda_p < L$, where L is a characteristic dimension of the medium filled by the plasma, λ_e, and λ_p are the mean free path lengths of electrons and ions) Eqs. (1) and (2) transform to

$$v_{e\varphi} - v_{g\varphi} = -D_{\varphi r}^e \frac{d}{dr}\ln n, \quad (3)$$

$$v_{p\varphi} - v_{g\varphi} = D_{\varphi r}^p \frac{d}{dr}\ln n, \quad (4)$$

where 1)

$$D_{\varphi r}^e = -D_a(0)\frac{\omega_e\tau_e}{1+\omega_e\tau_e\omega_p\tau_p}, \quad (5)$$

$$D_{\varphi r}^p = D_a(0)\frac{\omega_p\tau_p}{1+\omega_e\tau_e\omega_p\tau_p} \quad (6)$$

(D_a is the bipolar diffusion coefficient).

In the transition to lower pressures ($\lambda_e > L$, $\lambda_p > L$) the distribution of carriers over the cross

1)The symbol $D_{\varphi r}^e$ must be read: the diffusion coefficient D of electrons e in the direction ϕ produced by the concentration gradient n in the direction r; the definition of $D_{\varphi r}^p$ is similar.

section is more uniform and we can take

$$|E| \gg |(kT_e/e)\, d \ln n/dr|;$$

(1) and (2) transform to

$$v_{e\varphi} - v_{g\varphi} = \omega_e \tau_e^2 \frac{e}{m_e} E/(1 + \omega_e^2 \tau_e^2), \quad (7)$$

$$v_{p\varphi} - v_{g\varphi} = \omega_p \tau_p^2 \frac{e}{m_p} E/(1 + \omega_p^2 \tau_p^2). \quad (8)$$

Equations (1)—(6) contain the azimuthal component of the velocity of the neutral gas $v_{g\varphi}$, which is generally not equal to zero [3] and whose value must be substituted in the formulas mentioned. The value of $v_{g\varphi}$ has been measured spectroscopically, [3] but not for those pressures for which the present research was carried out (< 0.5 mm Hg). Therefore, we shall estimate $v_{g\varphi}$ theoretically in the outer region of the plasma where we have measured the desired quantities.

In the case of the measured and higher pressures ($\lambda_g \ll L$) we shall assume the usual condition in the theory of a viscous gas: $v_{g\varphi} = 0$ close to the wall. In the case of a rarefied gas ($\lambda_g \gtrsim L$) the velocity of the gas close to the wall is not equal to zero and is determined by the formula $v_{g\varphi}^0 = \zeta' \, \partial v_{g\varphi}/\partial r$, where ζ' is the collision coefficient—a quantity of the order of λ_g. We shall estimate $v_{g\varphi}^0$ by an example: $p = 10^{-2}$ mm Hg, $\zeta' \approx 5 \times 10^{-3}$ m. We then have $v_{p\varphi}^0 \approx 0.5$—5 m/sec.

Since the minimum velocity of "Hall" diffusion in ions, measured under the given conditions, is $v_{p\varphi} \sim 10^1$—10^2 m/sec, and the common error in the measurement of azimuthal velocities of ions is of the order of 30%, then the velocity of the neutral gas $v_{g\varphi}$ under our conditions is less than the possible error in the determination of $v_{p\varphi}$; since $v_{e\varphi} \gg v_{p\varphi}$, then it is even more true that $v_{e\varphi} \gg v_{g\varphi}$. Consequently, by discarding the quantity $v_{g\varphi}$ in Eqs. (1)—(4), (7), (8) under the concrete conditions of our measurements, we make a comparatively small error in the calculation of $v_{p\varphi}$ and an entirely negligible one in the evaluation of $v_{e\varphi}$.

The ratio of the velocities of transverse diffusion of electron and ions $|v_{e\varphi}|/|v_{p\varphi}|$ is different in the various regimes of the plasma.

1. State of bipolar diffusion: $\lambda_e, \lambda_p < L$; nonconducting walls. It follows from (3) and (4) that

$$|v_{e\varphi}| / |v_{p\varphi}| = \omega_e \tau_e / \omega_p \tau_p. \quad (9)$$

2. Intermediate case: $\lambda_e > L$, $\lambda_p < L$; B and p are such that $\omega_e \tau_e \gg 1$, $\omega_p \tau_p < 1$. It follows from (7), (8) that

$$|v_{e\varphi}| / |v_{p\varphi}| = 1/\omega_p^2 \tau_p^2, \quad (10)$$

i.e., the ratio of the velocities is proportional to the square of the pressure of the neutral gas.

3. The case of very low pressures: $\lambda_e, \lambda_p > L$ and weak fields: $\omega_e \tau_e \gg 1$, $\omega_p \tau_p > 1$. In this case, we get from (7) and (8) that

$$|v_{e\varphi}| = |v_{p\varphi}| = c_0 E/B, \quad (11)$$

i.e., their ratio is equal to unity; it does not depend on the pressure of the neutral gas.

The coefficients of transverse diffusion $D_{\varphi r}^e$ and $D_{\varphi r}^p$, according to (5) and (6), depend on the magnetic induction, and pass through a maximum for $\omega_e \tau_e \omega_p \tau_p = 1$. For $\omega_e \tau_e < 1$ and $\omega_p \tau_p < 1$, the quantities $D_{\varphi r}^e, D_{\varphi r}^p \sim 1/p^2$; for $\omega_e \tau_e \gg 1$, $\omega_p \tau_p > 1$, they do not depend on the pressure. For $\omega_e \tau_e \ll 1$, $\omega_p \tau_p \ll 1$, the coefficients of "Hall" diffusion decrease with increase in the molecular weight of the gas, according to the law $D_{\varphi r}^e \sim 1/M$, $D_{\varphi r}^p \sim 1/M^2$. For $\omega_e \tau_e \gg 1$ and $\omega_p \tau_p \gg 1$ we have $D_{\varphi r}^e = \text{const}$ and $D_{\varphi r}^p \sim 1/M$.

In addition to the change in $D_{\varphi r}$, the magnetic field also produces a redistribution of the charged particle concentration over the cross section: $n(r) = n(r, B)$.

In the present work, the velocities $v_{e\varphi}$ and $v_{p\varphi}$, and the coefficients $D_{\varphi r}^e$ and $D_{\varphi r}^p$ of transverse diffusion of electrons and ions were determined experimentally in inert gases under different conditions. The experimental results thus obtained are compared with theoretical derivations.

2. EXPERIMENTAL METHOD

A plasma was generated in a cylindrical tube by means of an arc from a heated cathode; the current was directed along the tube on the z axis. The magnetic field produced by the azimuthal drift of the particles was also directed along the z axis. The following were sealed in the tube: a) a double plane probe, parallel to the z, r plane; b) a cylindrical movable probe, parallel to the z axis. A directed double probe (of two metal plates of size 3.5×3.5 mm^2 joined together, interlaid with insulators and glazed at the end faces), set perpendicular to the wall, made it possible to determine the azimuthal component of the current of electrons or ions. [4] For this purpose, the current difference on the two sides of the twin probe was measured by means of a balance circuit. According to the theory of directed probes, [5-7] the difference in the current on the two sides of the twin plane probe in the given case is equal to

$$I_p(0) - I_p(\pi) = j S_p,$$

where j is the directed current density, and S_p is the effective collecting surface of one side of the probe. By applying positive and negative potentials, relative to the plasma, to the probe as a whole, we determined the values of $j_{e\varphi}$ and $j_{p\varphi}$.

The cylindrical movable probe served for the determination of the local concentration of charged particles and their gradient along the radius. The concentration of electrons and ions in the magnetic field was found by the method of Bickerton and Engel:[8] initially, n was determined from the probe characteristic (by Langmuir[9]), for B = 0; then the change in j_0 was measured for application of the field, and also the change in n corresponding to it. But, in contrast with Bickerton and Engel, the change in n, in accord with Schulz and Brown[10] was taken to be, on the whole, proportional to j_p, which depends on the rarefaction of the gas.[2)]

By thus determining $j_{e\varphi}$, $j_{p\varphi}$, n, dn/dr, we could compute $v_{e\varphi} = j_{e\varphi}/en$, $v_{p\varphi} = j_{p\varphi}/en$, and then

$$D^{e}_{\varphi r} = \frac{v_{e\varphi}}{d\ln n/dr}, \qquad D^{p}_{\varphi r} = \frac{v_{p\varphi}}{d\ln n/dr}. \qquad (12)$$

3. RESULTS

The investigation was carried out with inert gases. A tube of length L ~ 0.7 m, diameter 0.030 m was filled with inert gases at a pressure from 1.3 to 65 N/m² (0.01 to 0.05 mm Hg). The current through the tube was varied from 0.5 to 1.5 A; the field B, from 0.075 to 0.08 Wb/m².

The magnetic field dependence of the drift velocities of the charged particles in the azimuthal direction in helium is shown in Fig. 1. In the range of fields studied by us (up to 0.075 Wb/m²), the velocities of azimuthal diffusion increase with the field B somewhat more strongly than according to a linear law. $v_{e\varphi}$ is seen to be two orders of magnitude larger than $v_{p\varphi}$.

Experimental data are shown in Table I for argon at a pressure p = 45 N/m² and intensity of current through the tube I_a = 1.5 A at a point located at a distance of 10 mm from the axis (center of the plane probe).

Figure 2 gives the results of similar measurements in argon at another point (at a distance of

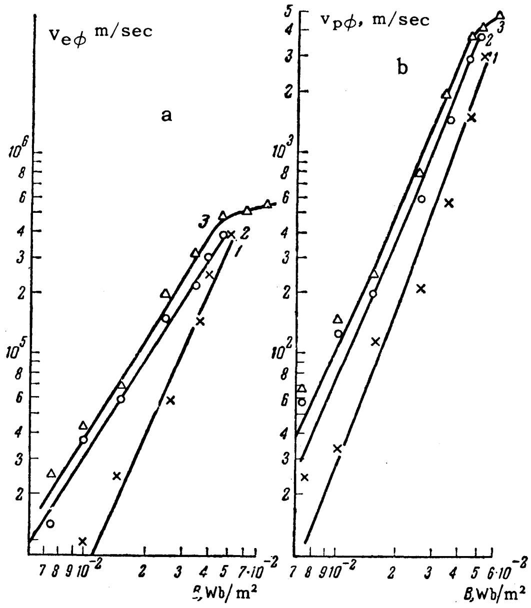

FIG. 1. Dependence of the velocity of azimuthal diffusion of charged particles in a plasma on the value of the applied magnetic field for different values of I_a. Gas – helium, p = 32.5 N/m². Curve 1 – I_a = 0.5 A, 2 – I_a = 1 A, 3 – I_a = 1.5 A.

8 mm from the axis)[3)] for different pressures of the neutral gas. As is seen from Fig. 2a, the velocity of the azimuthal drift of electrons passes through a maximum with increase in B in two cases: for p = 6.3 N/m² ($B_{max} \approx$ 0.03 Wb/m²) and for p = 1.55 N/m² (B ≈ 0.015 Wb/m²). For p = 41 N/m², the curve does not have a maximum

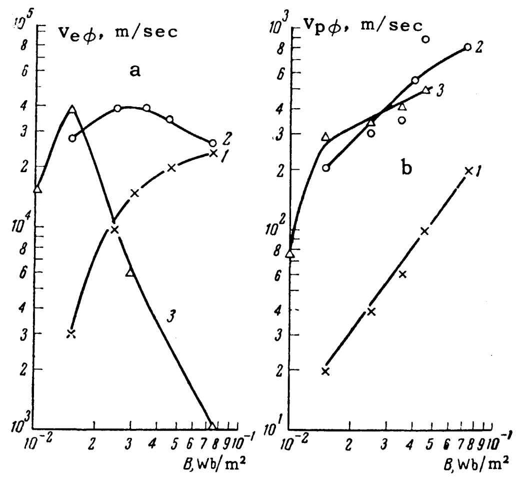

FIG. 2. Dependence of the velocity of azimuthal diffusion of ions and electrons in argon on the value of the field B for different pressures of the argon. I_a = 1.5 A. Curve 1 – p = 41 N/m², 2 – p = 6.3 N/m², 3 – p = 1.55 N/m².

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2)It was shown in [10] that the ion saturation current in the probe was not proportional to the concentration of charged particles but, depending on the ratio of the mean path length of the ion λ_p and the thickness of the layer δ, has the following characteristics: for $\lambda_p > \delta$, the current $j_p \sim n^{0.8}u_p^{0.55}$; for $\lambda_p \sim \delta$, the value of j is $\gamma_p \sim n^{0.58}u_p^{0.63}$, and for $\lambda_p < \delta$, the current is $j_p \sim n^{0.71}u_p^{0.57}$.

3)The data shown in the following graphs (3-5) refer to this same distance of 8 mm.

Table I

	$10^2 B$, Wb/m²						
	1.2	2.5	3.5	4.5	6.2	7	7.5
$10^{-4} j_{e\varphi}$, mA/m²	0.39	0.87	1.4	3.3	4.5	5.6	7.5
$10^{-4} j_{p\varphi}$, μA/m³	2.0	3.6	6.7	10	12	15	18
$10^{-16} n$, m⁻³	1.6	1.5	1.4	1.3	1.3	1.4	1.4
$10^{-2} d\ln n/dr$, m⁻¹	2.6	3.9	5.6	8.4	9.6	27	66
$10^{-3} v_{e\varphi}$, m/sec	1.5	3.5	6.1	15	20.1	25	33
$10^{-1} v_{p\varphi}$, m/sec	0.75	1.5	2.8	4.4	5.5	6.6	8.0
$D^e_{\varphi r}$, m²/sec	6	9.1	11	18	21	9.5	5
$10^2 D^p_{\varphi r}$, m²/sec	3	3.8	5.1	5.2	5.7	2.5	1.2

in the given range of field variation; it probably occurs at higher values of the field. The ion azimuthal velocities (Fig. 2b) do not reach a maximum in the range of fields studied by us.

A comparison of the velocities $v_{e\varphi}$ and $v_{p\varphi}$, found at a distance of 8 mm from the axis (Fig. 2, curve 1) and at a distance of 10 mm (Table I), shows that the velocity values at these two points can differ by a factor of 2—2.5. This is explained by the path of the dependence of the concentration n(r) in the presence of the constriction brought about by the magnetic field, and by the resulting difference in the values of d ln n/dr at different points over the cross section of the tube.

In the case of neon, as is seen from Fig. 3a, the value of $v_{e\varphi}$ has maxima for p = 3.25 N/m², $B_{max} \approx 0.01$ Wb/m² and for p = 10.5 N/m², $B_{max} \approx 0.025$ Wb/m². The value of B here also increases with the gas pressure. The ion azimuthal velocities in neon (Fig. 3b) do not pass through a maximum in this range of variation of the field B.

A comparison of the magnetic induction dependence of the measured and computed [by Eqs. (5), (6)] coefficients of Hall diffusion of electrons and ions in argon is given in Fig. 4. For p = 6.3 N/m², as is seen from Fig. 4a, the experimental curves have a maximum for B ≈ 0.015 Wb/m², the theoretical curves, for a somewhat large B ($B_{max} \approx 0.02$ Wb/m²). In contrast with the velocities $v_{e\varphi}$ and $v_{p\varphi}$, the diffusion coefficients are shown to be practically identical at the different points of the cross section of the plasma. For p = 41 N/m², as follows from Figs. 4c and d, the experimental curves pass through a maximum at B = 0.062 Wb/m², while the computed curves have a maximum for B = 0.059 Wb/m².

Figure 5 shows the values of $D^e_{\varphi r}$ and $D^p_{\varphi r}$ in helium as a function of the field B for p = 32.5 N/m². The experimental values of these quantities have a maximum for B = 1.5 × 10⁻³ Wb/m², the

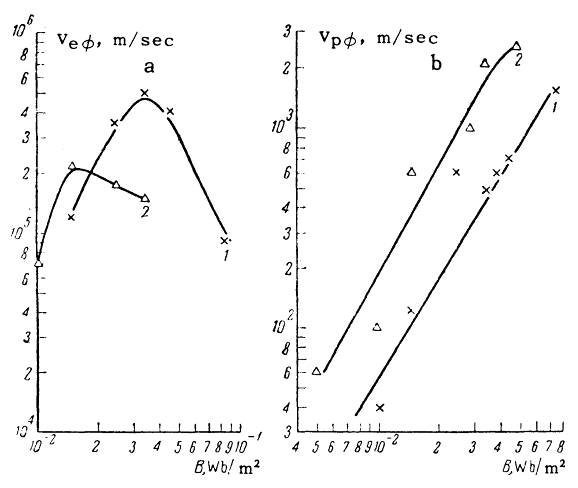

FIG. 3. Dependence of the velocity of azimuthal Hall diffusion of charged particles on the magnetic field in neon, I_a = 1.5 A; curve 1 – p = 10.5 N/m², 2 – p = 3.25 N/m².

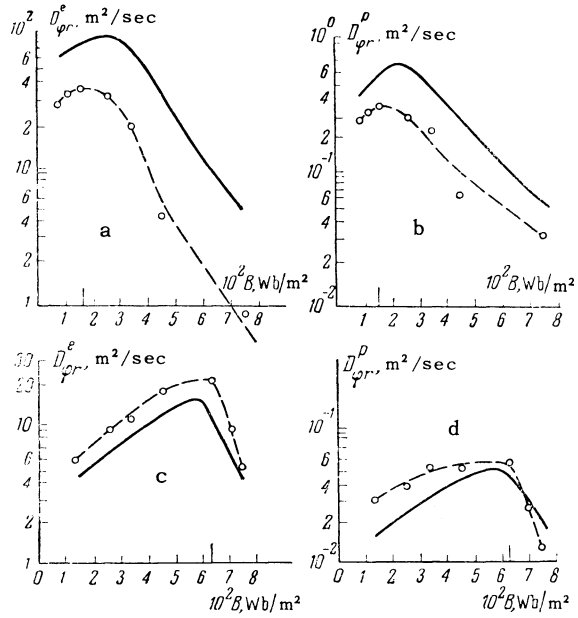

FIG. 4. Coefficients of transverse (Hall) diffusion of electrons and ions according to (12) as functions of the field for two pressures of argon: a, b – p = 6.3 N/m²; c, d – p = 41 N/m²; I_a = 1.5 A. The dashed curves are experimental, the solid curves are computed by Eqs. (5) and (6).

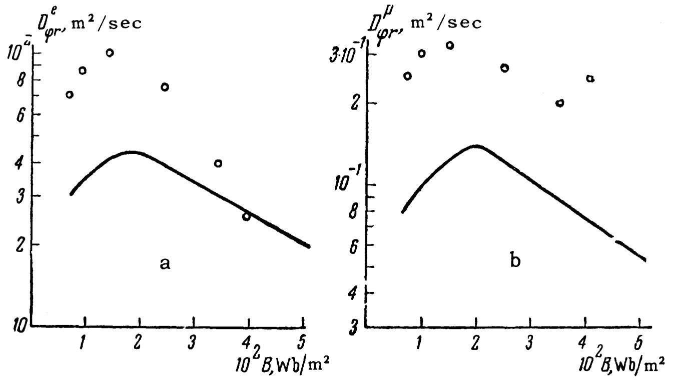

FIG. 5. Coefficient of the Hall diffusion of electrons and ions in helium as functions of the field B: p = 32.5 N/m², I_a = 1 A. The points are experimental data, the continuous curve is computed.

computed curve passes through a maximum for $B = 2 \times 10^{-3}$ Wb/m².

The maximum error of a single measurement for B = 0.06 Wb/m² was not greater than 30 per cent. For larger B, an individual measured value can exceed the real value by a factor of 2 (because of the effect of the magnetic field on the random ion current, determined by the probe).

IV. DISCUSSION OF THE RESULTS

A. We compare the values of the transverse Hall diffusion coefficients $D^e_{\varphi r}$ and $D^p_{\varphi r}$ (determined by us in argon for various B) with the values computed theoretically according to Eqs. (5) and (6) (see Fig. 4). In the calculation of the absolute values of $D^e_{\varphi r}$ and $D^p_{\varphi r}$, we make use of data on the ion mobility and on the probability of collisions with atoms of the neutral gas taken from the book by Brown.[1] The value of T_e was measured by us by the method of Bickerton and Engel.[8] It is seen from Eqs. (5) and (6) that the coefficients of transverse diffusion, in contrast with the coefficients of bipolar diffusion D_a, must at first increase linearly with increase in field (so long as $\omega_e\tau_e\omega_p\tau_p < 1$), and then, passing through a maximum, fall off as B^{-1} (for $\omega_e\tau_e\omega_p\tau_p > 1$). Our measurements show that $D^e_{\varphi r}$ and $D^p_{\varphi r}$ actually have maxima: for p = 6.3 N/m² the maximum corresponds to $B \approx 1.5 \times 10^{-2}$ Wb/m², when $\omega_e\tau_e\omega_p\tau_p \approx 0.86$; at high pressure, p = 41 N/m², the maximum advances for the much larger field $B \approx 6.2 \times 10^{-2}$ Wb/m² which corresponds to $\omega_e\tau_e\omega_p\tau_p \approx 1.2$. Consequently, upon increase in the pressure, the maximum is shifted to higher fields. The entire path of the dependence of $D^e_{\varphi r}$ and $D^p_{\varphi r}$ on the magnetic field is in excellent agreement with the conclusions from classical diffusion theory. The computed absolute values of $D^e_{\varphi r}$ and $D^p_{\varphi r}$ differ from those measured by us by a factor of 1.5–2.

The dependence of the coefficients $D^e_{\varphi r}$ and $D^p_{\varphi r}$ on the magnetic field can be expressed by a general formula

$$\eta = 2\xi/(1+\xi^2), \tag{13}$$

if we transform to the nondimensional variables

$$\xi = \frac{e}{c_0}\sqrt{\frac{\tau_e\tau_p}{m_e m_p}}\,B,$$

$$\eta_e = \frac{D^e_{\varphi r}}{D_a(0)}\sqrt{\frac{\tau_e m_p}{\tau_p m_e}}, \qquad \eta_p = \frac{D^p_{\varphi r}}{D_a(0)}\sqrt{\frac{\tau_p m_e}{\tau_e m_p}}.$$

Figure 6 shows the theoretical curve $\eta = \eta(\xi)$ and the values of $D^e_{\varphi r}$ and $D^p_{\varphi r}$ determined experimentally are shown for helium and argon. As is seen from the drawing, for $\omega_e\tau_e\omega_p\tau_p < 1$, the experiment essentially agrees with theory. For $\omega_e\tau_e\omega_p\tau_p > 1$ the experiment gives a value smaller than follows from the theory. Such a deviation from the law (13) can be explained if we take it into account that the strong magnetic field affects the motion of the ions and through them brings an error into the determination of the gradient of the ionic concentration, used in the calculation of D. Also the decrease in T_e with increase in B can play some role in the decrease of D.

B. In the range of fields B studied by us, the velocities of azimuthal diffusion of electrons and ions in the gas increase more strongly than by a linear law (see Fig. 1). As has already been shown above, the coefficients of transverse diffusion cannot increase for increase in the field more rapidly than according to a linear law. Therefore, the more rapid increase of $v_{e\varphi}$ and $v_{p\varphi}$ can be explained according to Eqs. (3) and (4) if we take it into account that at the middle of the radius of the tube (where the measurements were carried out) the field B generates a redistribution of the concentration of charged particles, such that the relative gradient increases (a constriction of the plasma column takes place).

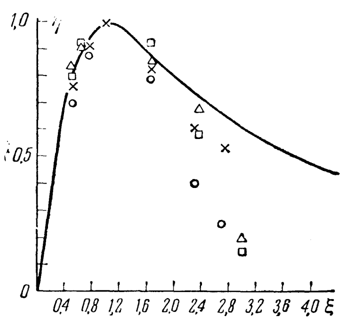

FIG. 6. Diffusion coefficients from experiment and from theoretical calculations. The points are experimental: ○ – $D^e_{\varphi r}$, × – $D^p_{\varphi r}$ for helium; □ – $D^e_{\varphi r}$, △ – $D^p_{\varphi r}$ for argon; the continuous curve is the theoretical curve.

Table II

		He	Ne	Ar
$10^{-4} v_{e\varphi}$, m/sec	Experiment	16	5.2	1.4
$v_{e\varphi}/v_{e\varphi}$(He)	Experiment	1	0.33	0.087
$v_{e\varphi}/v_{e\varphi}$(He)	Theory, according to(5)	1	0.13	0.034
$10^{-2} v_{p\varphi}$, m/sec	Experiment	9	2.05	0.38
$v_{p\varphi}/v_{p\varphi}$(He)	Experiment	1	0.21	0.044
$v_{p\varphi}/v_{p\varphi}$(He)	Theory, according to (6)	1	0.15	0.013

C. We now compare the values of $v_{e\varphi}$ and $v_{p\varphi}$ in argon at three pressures: $p = 1.55$ N/m^2, $p = 6.1$ N/m^2, $p = 41$ N/m^2. In a magnetic field with induction $B = 5 \times 10^{-2}$ Wb/m^2, the pressure $p = 1.55$ N/m^2 corresponds to the condition $\omega_e\tau_e > 1$, $\omega_p\tau_p < 1$; $\lambda_e \geq L$, $\lambda_p < L$ (case 2 of the introduction) and Eq. (10) is used, according to which $|v_{e\varphi}|/|v_{p\varphi}| = 6.5$. The experiment gives $|v_{e\varphi}|/|v_{p\varphi}| \approx 5$. The pressures $p = 6.3$ and 41 N/m^2 correspond to the conditions $\lambda_e, \lambda_p < L$ — the regime of bipolar diffusion (case 1 of the introduction), in which the formula (9) is employed. From it we get $|v_{e\varphi}|/|v_{p\varphi}| \approx 130$. The experiment gives $|v_{e\varphi}|/|v_{p\varphi}| \approx 60$. We would have obtained case 3 of the introduction in argon at much lower pressures or much stronger fields.

D. We contrast the values of $v_{e\varphi}$ and $v_{p\varphi}$ in different gases for a given current $I_a = 1.5$ A and reduced field $B/p = 1.1 \times 10^{-3}$ Wb/m. As is seen from Table II, the velocities $v_{e\varphi}$ and $v_{p\varphi}$ fall off with increase in the atomic weight, but less slowly than follows from calculation.

V. CONCLUSIONS

1. The transverse motions of charged particles in a plasma column placed in a longitudinal magnetic field with induction B within the range 0—0.08 Wb/m^2, at a pressure $p \sim 3$—50 N/m^2, corresponding to the regime of bipolar diffusion in a plasma, obey the laws of "Hall diffusion" in pair collisions. The velocities of transverse diffusion of electrons are of the order of 10^3—10^5 m/sec, the velocities of the ions are of the order of 10—10^2 m/sec. These velocities decrease with increase in pressure and molecular weight of the gas, and pass through a maximum upon increase of the magnetic field. Moreover, they are strongly dependent on the radial coordinate of the point of observation.

2. Upon further rarefaction of the gas to a pressure ~ 1 N/m^2, the difference between the velocities of transverse drift of the electrons and ions decreases. Finally, at still lower pressures, corresponding to the Tonks-Langmuir plasma state, the transverse drift of the electrons and ions takes place with equal velocities, corresponding to formulas (7) and (8) of free drift motion.

3. The experimentally determined coefficients of transverse Hall diffusion in the bipolar diffusion state also fall off monotonically with increase in pressure and molecular weight, and pass through a maximum, upon increase in B, at $\omega_e\tau_e\omega_p\tau_p \approx 1$. Their absolute values are found to be in satisfactory agreement with those computed by Eqs. (5) and (6).

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Translated by R. T. Beyer
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