ACOUSTIC OSCILLATIONS AND THE KINETICS OF HEATING UP A HELIUM PLASMA AT LOW TEMPERATURES[1)]

I. Ya. FUGOL', G. P. REZNIKOV, and Yu. F. SHEVCHENKO

Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences

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The low-frequency oscillations of the radiation from a helium plasma upon cooling of the walls of the discharge tube by liquid helium are studied experimentally. The oscillations are interpreted as being a manifestation of standing sound waves produced in the plasma during high-frequency breakdown. The temperature of the plasma atoms was determined from the measured oscillation periods as a function of the excitation-pulse duration for various values of the discharge current and gas density. A calculation of the electron density and the heating kinetics was performed on the basis of elementary theory. Good qualitative and satisfactory quantitative agreement is observed between the calculations and the experiment. It is shown the observed oscillations can be used to find various plasma parameters.

1. INTRODUCTION

WE previously reported[1] the observation of low-frequency oscillations of the intensity of radiation of the helium plasma of a high-frequency discharge. The oscillations were observed upon cooling of the helium discharge vessel to low temperatures; their amplitude and period were the greater the lower the temperature of cooling. The oscillations were seen on all atomic lines and molecular bands of the radiation of the helium plasma and the characteristics of the oscillations of all lines and bands were the same for the same conditions of excitation. The frequencies of the observed oscillations amounted to tens of kilohertz and, as was shown in[1], were identical with the frequencies of the characteristic acoustic oscillations of the gas in the vessel. From the analysis of the experimental data in[1], it could be concluded that the oscillations of the radiation intensity were connected with the appearance of standing sound waves. Inasmuch as the speed of sound in the gas depends on its temperature, the measurement of the periods of the oscillations allows us to determine the temperature of the ions and the neutral gas directly at the time of the discharge pulse and after its termination. In other words, the investigation of such oscillations of the radiation intensity represents an experimental method of study of the kinetics of high-frequency heating of the neutral gas in a weakly ionized plasma. In[1], preliminary data were given on the change in the temperature of the gas as a function of the dimensions of the vessel and other experimental conditions. It should be noted that the non-monotonic change in the intensity of the radiation of the helium plasma at nitrogen temperatures (the appearance of an additional maximum) had been described by us as early as 1964.[2]

In a brief note, Berlande, Goldan and Goldstein[3] reported that they observed similar oscillations in a measurement of the electron concentration in a cryogenic helium plasma.[2)] However, their treatment of the phenomenon differs somewhat from ours—they assumed that the oscillations are acoustic shock waves in the gas; a detailed discussion of the nature of this effect is lacking in[3]. It should be emphasized that upon creation of a plasma by a high-frequency discharge and comparatively small currents (of the order of one or even a fraction of an ampere), the sound oscillations in the gas are not observed at room temperature. Following excitation of the plasma by powerful current pulses (of the order of hundreds of amperes), Shukhtin and co-workers[4] noted local changes in the density of the gas in the vessel. Recently, at the II All-union Conference on the Physics of Low-temperature Plasma, Shukhtin and Kozlov[5] reported oscillations in the density and intensity of radiation of a helium plasma at room temperature (current pulses of tens and hundreds of amperes), similar to those oscillations which we had discovered in a cryogenic plasma.[1]

Sound oscillations in the plasma of a gas discharge of constant current at high gas temperature can also be excited by means of an additional high-frequency pulse of high local intensity. The generation and propagation of sound in cylindrical vessels has been studied by such a method in a series of works by Hayess.[6]

In the present work, we report the results of the calculation and a detailed description of experiments on the excitation of sound oscillations and the kinetics of pulsed heating of a cryogenic helium plasma of low pressure with small discharge currents.

2. EXPERIMENT

The study of the oscillations of the intensity of radiation of the helium plasma was carried out on apparatus whose schematic diagram is shown in Fig. 1. High-frequency electrode-less discharge with frequency f = 8 MHz was excited in unsealed glass retorts. The

[1)]Reported at the II All-union Conference on the Physics of Low-temperature Plasma (Minsk, November, 1968).

[2)]No reference was made in [1] to these authors because we learned of the research of [3] only after publication of our paper.

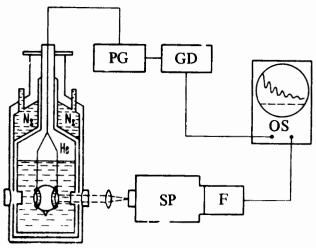

FIG. 1. Schematic drawing of experiment: PG – high-frequency pulse generator; GD – generator of delayed pulses, G5-4B; OS – S1-8 oscillograph; SP – spectrograph DFS-8, F – photomultiplier FÉU-64 with cathode follower.

retorts of molybdenum glass were evacuated to 10^{-7} mm Hg, carefully annealed, filled with spectrally pure helium, and sealed. Retorts were prepared with different helium pressures[3)]—from 1 ($N = 3.6 \times 10^{16}$ cm^{-3}) to 40 ($N = 1.4 \times 10^{18}$ cm^{-3}) mm Hg. In this range of pressures, the afterglow of the helium plasma is most intense. The discharge vessel, together with ring electrodes, was placed inside a metal cryostat which had an optical window. The retorts were immersed directly in liquid helium or liquid nitrogen.

To excite a discharge, a high-frequency generator was used, which consisted of a push-pull circuit of GI-30 tetrodes. The generator produced rectangular current pulses and made it possible to change the length and frequency of the sequence of pulses without change in the value of the discharge current. The measurements were made for different pulse lengths from 4 to 200 μsec; the repetition frequency ranged from 30 to 5 Hz. Excitation of the plasma by single pulses was also used.

Ignition of the discharge and establishment of the current through the plasma, as current oscillograms show, take place within a fraction of a microsecond. Within one or two microseconds after the beginning of the pulse, the resistance of the plasma is already much less than the internal resistance of the generator, which amounts to several kilohms. Actually, the resistivity of the plasma

$$1/\sigma = m/ne^2\tau_{ea} \tag{2.1}$$

for electron concentrations $n \approx 10^{12}$ cm^{-3}, which are characteristic in our experiments, amounted to

$$1/\sigma = 9.2\cdot 10^{-12}\, p \text{ sec} = 8.3\, p \text{ ohm-cm} \tag{2.2}$$

Here p is the pressure in mm Hg, τ_{ea} is the mean time between elastic electron-atom collisions and is given by

$$\tau_{ea} = 1/N\langle q_{ea}v_e\rangle, \tag{2.3}$$

q_{ea} is the elastic scattering cross section of electrons by atoms, v_e the velocity of the electrons, N the concentration of atoms, ⟨ ⟩ denotes averaging over the velocities. For electrons with energies of the order of several electron volts, as follows from the experimental data (see[7]), the value of $\langle q_{ea}v_e\rangle$ does not depend on the electron temperature and is equal to

$$\langle q_{ea}v_e\rangle \approx 6\cdot 10^{-8}\,\text{cm}^3\text{-sec}^{-1} \tag{2.4}$$

Consequently,

$$\tau_{ea} = 4.7\cdot 10^{-10} p^{-1} \text{ sec} \tag{2.5}$$

The total resistance of the discharge column is approximately equal to

$$R_{\text{pl}} \approx 2p \text{ ohm} \tag{2.6}$$

(the length of the discharge column amounted to ~3 cm, and the area 12 cm^2). Even for maximum pressure p = 40 mm Hg, the total resistance did not exceed 100 ohm, i.e., it was one-tenth the internal resistance of the generator. Therefore the value of the discharge current through the plasma was determined by parameters of the external circuit.

All the measurements were usually carried out at two voltages—2.1 and 3.6 kV. The oscillographic measurements for these voltages give values of the current of 1 and 2.3 A in the pulse, respectively. It should also be observed that in the high-frequency excitation of the plasma of frequency f = 8 MHz, the skin depth is much greater than the dimensions of the discharge vessel. An estimate of the thickness of the skin layer for the values of the resistivity (2.2) given above yields the value

$$\delta = c/2\pi(2f\sigma)^{1/2} = 3.6\, p^{1/2} \text{ cm}, \tag{2.7}$$

where c is the speed of light. In other words, the high-frequency excitation and heating of the plasma take place throughout the volume.

Spectral measurements were made by means of a spectrograph and a photomultiplier (FÉU-64), with a cathode follower. The generator G5-4B triggered the sweep of the S1-8A oscillograph at any moment of the afterglow, which made it possible to measure the later afterglow with large gain and excellent time resolution.

The intensity of the radiation of different atomic lines and molecular bands of the helium plasma was measured experimentally at the time of the pulse (glow) and after its end (afterglow). The dependence on time both of the radiation and the afterglow at low temperatures reveals a periodic oscillation. It is possible to observe up to 10–12 periodic oscillations. (At a later instant of time, the afterglow is too small.)

Figure 2 shows, as a qualitative illustration, an oscillogram of the intensity oscillations of the afterglow for the band λ = 4650 Å. The period and amplitude of the oscillations depend on the conditions of cooling and the dimensions of the discharge vessel, the current, the length of the excitation pulse, and the density of the gas. We did not succeed in observing oscillations in the radiation of the helium plasma at room temperature. Upon cooling of the discharge vessel by liquid nitrogen, oscillations of the intensity with relatively small amplitude were observed. The period of oscillations for a spherical column with R = 2 cm amounted to 40–50 μsec. The oscillations had maximum intensity, and their period increased to 180–200 μsec, upon cooling of the vessel to liquid helium temperature. The dimensions and the shape of the discharge vessel had an important effect on the period of oscillations. The corresponding illustrations of the effect of the cooling temperature and of the dimensions of the discharge vessel are given in[1]. Figure 3 shows the oscillations of the intensity of the afterglow for a pressure of 25 mm Hg and for two values of the current. For a current of 1 A, the period of the oscillations is equal to ΔT = 190 μsec; for a current of 2.3 A, it amounted to ΔT = 140 μsec. A discussion of the experimental data on the dependence

[3)] Everywhere the pressures are referred to 293°K.

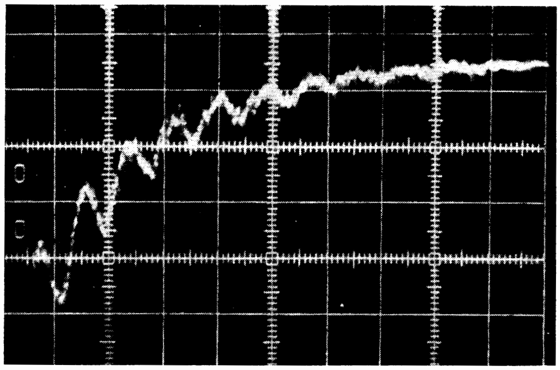

FIG. 2. Oscillogram of the oscillations of the intensity of the afterglow in helium plasma upon cooling of the discharge tube to 4°K (4650 Å band). $N = 3 \times 10^{17}\,cm^{-3}$, radius of retort, R = 2 cm, $\tau = 5\,\mu sec$ (along ordinate: intensity in arbitrary units, scale along the time axis, one unit corresponds to 200 μsec; O – start of sweep).

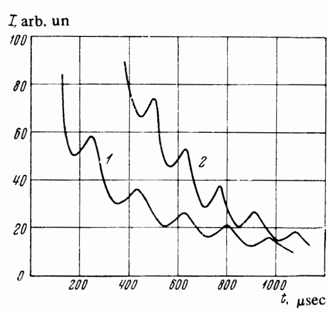

FIG. 3. Oscillations of the intensity of the afterglow (λ = 4471 Å) for different currents. Cooling of the discharge tube to 4°K, $\tau = 5\,\mu sec$, R = 2 cm, $N = 9 \times 10^{17}\,cm^{-3}$ (p = 25 mm Hg); curve 1 – i = 1 A, 2 – i = 2.3 A.

of the period of oscillations on the current, pressure and pulse length will be given in Sec. 5.

3. THE NATURE OF THE LOW-FREQUENCY OSCILLATIONS IN THE RADIATION

The afterglow of all the lines and the bands in the helium high-frequency discharge is the result of different processes of recombination of the electrons with atomic or molecular ions in the plasma. Therefore, the oscillations of the intensity of radiation are determined by the oscillations of the density of the individual components of the plasma. It is quite evident that these oscillations cannot be longitudinal Langmuir oscillations, inasmuch as the frequency of the latter f_L is too great:

$$f_L = (ne^2/\pi m)^{1/2} = 0.9\cdot 10^4 n^{1/2} \sim 10^{10}\,\text{Hz} \qquad (3.1)$$

when $n \sim 10^{12}\,cm^{-3}$. Ion acoustic oscillations also do not explain the observed oscillations of the intensity. The frequency of the ion sound

$$f_i \approx (kT_e/MR^2)^{1/2} \qquad (3.2)$$

for values of the electron temperature of the order of several electron-volts, is seen to be larger than several megahertz, i.e., is tens and hundreds of times greater than the experimentally observed frequencies.

The observed frequencies lie in the range of the eigenfrequencies of the sound oscillations of the gas in the discharge tube. In our opinion, low-frequency modulation of the radiation is due to acoustic oscillations arising at the moment of high-frequency breakdown. The problem of the mechanism of the appearance of acoustic oscillations is very complex. It can be shown that there are at least two reasons for sound excitation. One of these is that an electrodynamic pressure pulse arises at the moment of breakdown in the gas. The other reason may be the local pulsed heating of the gas in breakdown. The electrodynamic Lorentz force $F = c^{-1}H$ is equivalent to an additional magnetic pressure

$$p' = H^2/8\pi = i^2/2\pi c^2 r^2, \qquad (3.3)$$

where $i = j\pi r^2$ is the total current through the discharge at the moment of breakdown, r the radius of the breakdown channel, j the current density, and $H = 2i/cr$ the magnetic field of the current. The relative amplitude of the oscillations in the sound wave

$$p'/p_0 = i^2/2\pi c^2 r^2 NkT \qquad (3.4)$$

is inversely proportional to the gas temperature, inasmuch as the equilibrium pressure at the temperature T is equal to $p_0 = NkT$. In order to explain the value of the observed relative amplitudes of the order of 0.1–0.3, it is necessary to assume that the discharge at the moment of breakdown takes place along a narrow channel with diameter of the order of one millimeter (for a current $i \approx 2$ A, $N = 2 \times 10^{17}\,cm^{-3}$, T = 4° K).

The relative amplitude of the oscillations from local pulsed heating is equal to $\delta T/T$ and is, just as the amplitude (3.4), inversely proportional to the gas temperature. Therefore, regardless of the mechanism of excitation, the relative amplitude of the oscillations of the gas density at liquid helium temperatures should be two orders greater than at room temperature. It can be supposed that the fact that it is not possible to observe modulation of the radiation by sound oscillations at room temperature in a weak high-frequency discharge is explained by just this effect. The problem of the excitation and damping of sound is analyzed in more detail in[8].

The pressure pulse arising at the moment of breakdown leads to the formation of standing sound waves in the tube. In a spherical resonator, the frequency of the fundamental form of the oscillations is equal to (see, for example,[9]),

$$f = 4.49\,s/2\pi R, \qquad s = (\gamma kT/M)^{1/2}, \qquad (3.5)$$

where s is the adiabatic sound speed, $\gamma = c_p/c_v = 5/3$. The period of these oscillations is

$$\Delta T = \frac{1.4R}{s} = \frac{238}{\sqrt{T}}R \ \ \mu\text{sec} \qquad (3.6)$$

where R is given in centimeters and T in °K. For example, for T = 4.2°K and R = 2 cm, the period of the sound oscillations amounts to ΔT = 230 μsec, for T = 77°K, it is ΔT = 54 μsec. These values of the periods are in excellent agreement with experimental data in the case of cooling both to liquid helium and to liquid nitrogen temperatures. However, the agreement of the calculated and experimental values of the periods is satisfactory only for small discharge currents and limitingly short excitation pulses, when little gas heating takes place in the discharge tube. For large currents and long pulses, heating of the gas takes place during the pulse and its mean temperature will be different from the temperature of the walls of the vessel. Therefore, by measurement of the period of the oscillations, we can determine the gas temperature immediately after the end of the pulse, and thus study the kinetics of the high-frequency heating of the plasma.

4. KINETICS OF PULSE HEATING

In this section, we shall give the results of the calculation of the heating of a neutral gas on the basis of elementary theory. In our experiments, the limiting case

$$\omega\tau_{ea} \ll 1 \tag{4.1}$$

is realized, inasmuch as the operating frequency $\omega = 5 \times 10^7\ \text{sec}^{-1}$, while $\tau_{ea} \sim 10^{-9}-10^{-10}$ sec (see (2.5)). Therefore, the discharge can be regarded as quasistatic. Elevation of the gas temperature during the pulse takes place by collisions of hot electrons with atoms. According to[10], the change in the mean energy of the gas per unit time is described by the equation

$$N dT / dt = \delta\nu_{ea} n(T_e - T). \tag{4.2}$$

Here $\delta = 2m/M$ is the inelasticity coefficient, which determines the fraction of the energy given up to the atom in elastic collisions, $\nu_{ea} = 1/\tau_{ea}$. In Eq. (4.2), we neglect cooling of the gas due to thermal conduction. This process is slow and is characterized by the time constant Λ^2/D_{sd}, where D_{sd} is the coefficient of self-diffusion of helium atoms, $\Lambda = R/\pi$ is the diffusion length of the vessel. The value of the self-diffusion coefficient for helium is well known[11] and is described by the approximate formula $D_{sd} = 60T^{1/2}p^{-1}$ (T in °K, p the reduced pressure in mm Hg). The time of cooling for a spherical retort with R = 2 cm for 10°K amounts to 2p [μsec], which is a hundred times greater than the duration of the excitation pulses.

For the solution of Eq. (4.2), it is necessary to know the change with time of the electron density n and their temperature T_e. The change in the electron concentration with time is determined by the competition between ionization and processes of surface and volume recombination. We shall describe the number of acts of ionization phenomenologically, following Braginskii and Migdal, with the help of the energy "value" of the electron, ϵ_0. The parameter ϵ_0 is the mean energy that is required for the creation of a single electron in the discharge. The energy ϵ_0 is inversely proportional to the ionization coefficient γ. In the physics of a gas discharge, another quantity, $\eta = \gamma/E\langle v_e\rangle$ is frequently used. This is equal to the number of ionization events per volt (E is the intensity of the electric field in V/cm). The parameter η is a known (from experiment) function of the ratio E/p. The dependence of η on E/p has a maximum for E/p ~ 50–100 V/cm-mm Hg, while $\eta \approx 10^{-2}V^{-1}$[13]. The energy "value" ϵ_0 expressed in electron volts, is equal to $1/\eta$, i.e.,

$$\varepsilon_0 \approx 100\ \text{eV}. \tag{4.3}$$

The equation for the electron density is written in the form

$$\frac{dn}{dt} = \frac{j^2}{2\sigma\varepsilon_0} - \frac{D_a}{\Lambda^2}n - \alpha n N_i. \tag{4.4}$$

Here $f^2/2\sigma$ is the density of Joule heat, D_a is the coefficient of ambipolar diffusion, and the last term describes the volume recombination of electrons and ions. In the discharge, when the electron temperature is equal to several electron volts, the volume recombination is much less than the surface recombination due to ambipolar diffusion. Therefore we shall neglect volume recombination in what follows.

Finally, we write down the equation for the change of the electron temperature with time. The heating of the electrons takes place as the result of the release of the Joule heat. Their cooling is due to the transfer of energy to the neutral gas as the result of the small inelasticity δ in elastic collisions and in inelastic collisions—in the excitation of internal electrons of the atoms. The latter process is a threshold one (the threshold of excitation in helium exceeds 20 eV), and in the case in which the mean energy of the electrons is less than the excitation threshold, the fraction of the energy transferred per excitation and the subsequent radiation is small in comparison with the energy entering into heating of the gas. In our experiments, the mean temperature of the electrons does not exceed several electron volts and we can therefore assume that the cooling of the electrons generally takes place in elastic collisions. Consequently, the equation for the electron temperature can be represented in the form

$$\frac{d}{dt}(nkT_e) = \frac{j^2}{2\sigma} - \delta\nu_{ea} nk(T_e - T). \tag{4.5}$$

In this equation, we can neglect the change in the mean energy of the electrons with time, and set $d(nkT_e)/dt = 0$. Actually, the characteristic time of cooling of the electrons

$$\tau_э = \tau_{ea}/\delta = 1.7/p\quad \mu\text{sec} \tag{4.6}$$

in our experiments amounted to a fraction of a microsecond (p = 5–50 mm Hg). It is much less than the pulse length, the period of oscillation, etc. Therefore, at each instant of time, equilibrium is established almost instantaneously (after a time of the order of τ_0) between heating and cooling of the gas, i.e.,

$$j^2/2\sigma - \delta\nu_{ea} nk(T_e - T) = 0. \tag{4.7}$$

Using (4.7), we write the set of equations for heating the gas, and for the electron density in the form

$$dT/dt = j^2/2\sigma N k, \tag{4.8}$$

$$dn/dt = j^2/2\sigma\varepsilon_0 - (D_a/\Lambda^2)n. \tag{4.9}$$

We first consider the kinetics of the discharge for short pulses $\tau < \Lambda^2/D_a$, when the ambipolar diffusion still does not limit the growth of the electron density. In this case, at the instant of the end of the pulse, the electron concentration and the heating of the gas are equal to

$$n(\tau) = \frac{j}{e}\left(\frac{m}{\varepsilon_0\tau_{ea}}\tau\right)^{1/2}, \tag{4.10}$$

$$T - T_0 = \frac{\varepsilon_0}{Nk}n(\tau) = \frac{j}{Nek}\left(\frac{m\varepsilon_0}{\tau_{ea}}\tau\right)^{1/2}, \tag{4.11}$$

where T_0 is the gas temperature at the beginning of the pulse.

In the other limiting case $\tau > \Lambda^2/D_a$, a stationary electron density

$$n_0 = \frac{j}{e}\left(\frac{m}{2\varepsilon_0\tau_{ea}}\frac{\Lambda^2}{D_a}\right)^{1/2}. \tag{4.12}$$

is established. In this case, the heating of the gas depends linearly on the pulse length

$$T - T_1 = \frac{\varepsilon_0}{Nk}\frac{D_a}{\Lambda^2}n_0\tau = \frac{j}{Nek}\left(\frac{m\varepsilon_0}{2\tau_{ea}}\frac{D_a}{\Lambda^2}\right)^{1/2}\tau, \tag{4.13}$$

where T_1 is some constant. The transition from Eq. (4.11) to (4.13) takes place over a pulse length of the order Λ^2/D_a[4].

Equations (4.11) and (4.13) describe the increase in the gas temperature during a single pulse. After the end of the pulse, a slow cooling of the gas takes place as the result of the transfer of the excess heat on the walls of the container. The characteristic time of cooling is estimated at the beginning of this section and amounts to 2p [μsec].

5. DISCUSSION OF THE EXPERIMENTAL RESULTS AND COMPARISON WITH CALCULATIONS

As is seen from Fig. 3, the observed periods of the oscillations do not exceed 200 μsec and can be recorded reliably up to ten periods. In other words, the time during which the low-frequency oscillations are visible after the end of the excitation pulse amounts to 1—2 μsec. For large times, the afterglow is so weak that it cannot be recorded. Consequently, the time of observation of the oscillations is smaller by a factor of three or four than the characteristic time of cooling of the gas as the consequence of heat conduction. $\Lambda^2/D_{sd} \sim 2p$ [μsec]. Therefore, the temperature of the gas should change weakly during the time of observation. This conclusion is reinforced by experiment: the periods of oscillation in the afterglow remain virtually constant (see Fig. 3, for example). Thanks to this, we can reliably measure the gas temperature after the end of the excitation pulse. The experiments were carried out both with a single pulse and with periodically repeated pulses. The repetition frequency of the pulses amounted to 5 or 25 Hz and was so chosen that the interval between the pulses was several times greater than the cooling time. Therefore, at the instant of each successive pulse, the gas manages to cool to the temperature of the walls of the vessel. This fact was monitored by comparing the periods of the oscillations in the excitation by a single pulse and the excitation of a series of repeated pulses; in both cases the periods were identical.

The investigation of the oscillations of the glow in the time of the pulse is complicated by the heating of the gas, which takes place at the same time. Usually the magnitude and shape of the first period of oscillations in the glow differ markedly from those in the afterglow. Although one can observe several periods of oscillations in the glow, it has not been possible to extract reasonable information from them. This is connected with the fact that strong heating of the gas occurs in the case of very long pulse lengths. Even for the minimum current i = 1 A, the heating amounts to many tens of degrees, which leads to an unstable picture of the oscillations and to a large scatter of the experimental results. Such poor reproducibility of the results for $\tau > 150$ μsec is due to the large amount of heat that is introduced into the container and transferred in the bath to the liquid helium. As a consequence, and extraordinarily intense and nonstationary boiling of the helium in the cryostat takes place, gaseous bubbles are formed near the walls of the container and, consequently, the cooling conditions change in an uncontrolled manner. For such a large pulse length τ, a significant scatter of the results is also observed in the afterglow. Here the fact that the gas cannot be cooled at the moment of the next pulse plays an important role. Therefore, we shall limit ourselves to a discussion of the experimental data on the oscillations of the afterglow intensity for pulse lengths $\tau \lesssim 100$ μsec.

On the basis of the interpretation of the low-frequency oscillations of the sound vibrations in the plasma, we determine the gas temperature from the measured periods (see Eq. (3.6)). The heating of the gas was investigated as a function of the pulse length for different pressures (densities) of the gas and for different currents. Figures 4 and 5 show the curves for the dependence of the temperature of the atoms on the pulse length for various densities of helium and for two values of the current. The vertical bars through the experimental points characterizing the accuracy of the measured values of the temperature, are the limiting scatter of the results obtained in a large number of identical experiments. These experiments were carried out repeatedly in several retorts with identical helium densities. The limit of scatter of the data of the different measurements for the same conditions amounted to ± (15—20)% and increased with increase in the current and pulse length. The accuracy of the separate measurement of the period amounted to (3—5)% and of the temperature, ± (5—10)%.

It is seen from Figs. 4 and 5 that for short pulse lengths the temperature increases with growth of τ more slowly than for long pulses. For long pulses, the ex-

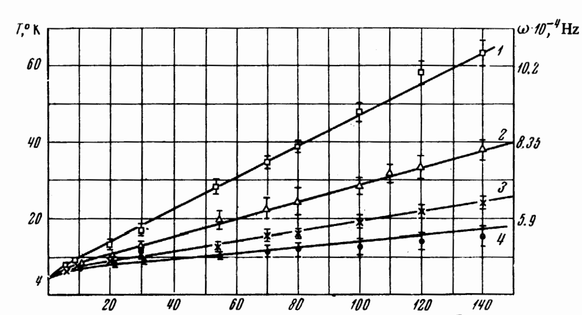

FIG. 4. Dependence of the mean gas temperature on the length of the exciting pulse τ for a current of i = 1 A and different pressures: 1 – $N = 3.1 \times 10^{17}$ cm^{-3} (p = 8.7 mm Hg), 2 – $N = 5.7 \times 10^{17}$ cm^{-3} (p = 16 m Hg), 3 – $N = 8.9 \times 10^{17}$ cm^{-3} (p = 25 mm Hg), 4 – $N = 1.2 \times 10^{18}$ cm^{-3} (p = 33.5 mm Hg). Scale at the right – value of the oscillation frequency. The vertical bars show the scatter of the experimental data for different measurements of the temperature.

[4] Here we neglect the weak temperature dependence of the coefficient D_a of ambipolar diffusion.

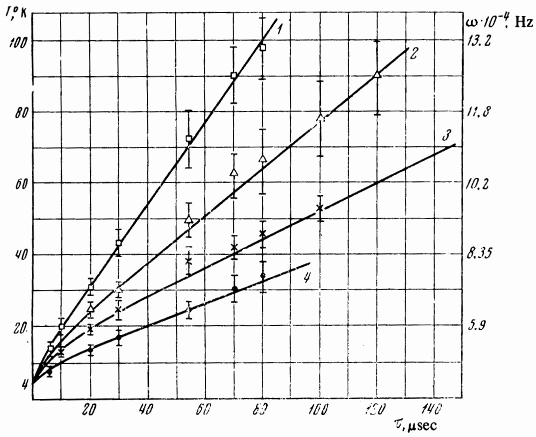

FIG. 5. Dependence of the mean gas temperature on the pulse length τ for a current of i = 2.3 A. Curves 1 – 4 correspond to the same gas densities as in Fig. 4.

perimental points cluster about the line

$$T = \text{const} + a_1\tau. \tag{5.1}$$

In the region of short pulses, the analysis of experimental results shows that the heating of the gas takes place according to the law

$$T - 4.2° \text{K} = a_{1/2}\sqrt{\tau}. \tag{5.2}$$

(The scale of Figs. 4 and 5 makes the region of small pulse lengths less lucid.) The coefficients $a_{1/2}$ and a_1, which characterize the rate of heating as a function of the pulse length, are functions of the current and gas density.

Figure 6 shows the results of the treatment of the experimental data of Figs. 4 and 5 for short pulse lengths by means of Eq. (5.2). The coefficient $a_{1/2}$ depends linearly on $p^{-1/2}$ and is directly proportional to the current. The ratio of the slope coefficients for currents i equal to 2, 3 and 1 A, is 2.2 ± 0.2, which is identical, within the limits of scatter of the experimental values, with the ratio of the currents. For a fixed current, the product $a_{1/2}\sqrt{p}$ is constant and is equal to $(11.6 \pm 1.8) \times 10^3$ deg-sec^{-1}-(mm Hg)$^{1/2}$ for a current of 2.3 A and $(5.2 \pm 1) \times 10^3$ for a current of 1 A.

The dependences of the temperature on the pulse length and of the coefficient $a_{1/2}$ on the current and pressure found in the experiment are in complete correspondence with the results of the calculation of the kinetics of heating for small values of τ. In accord with Eq. (4.11), the gas temperature should increase in proportion to $\tau^{1/2}$, and the coefficient of proportionality is

$$a_{1/2} = \frac{j}{Nek}\left(\frac{m\varepsilon_0}{\tau_{ea}}\right)^{1/2} \infty\, ip^{-1/2}. \tag{5.3}$$

Equation (5.3) permits a quantitative comparison of the experiment with the calculation. If we substitute the value ϵ_0 = 100 eV and τ_{ea} from (2.5) in Eq. (5.3), and take it into account that the current density $j = 1/\pi R_{eff}$, where $R_{eff} = 0.6\,R = 1.2$ cm is the radius of the ring electrodes, then the value of $a_{1/2}\sqrt{p}$ for i = 1 A is equal to 5×10^3 deg-sec$^{-1/2}$ (mm Hg)$^{1/2}$, which agrees surprisingly well with the experimental value (5.2 ± 1) $\times 10^3$.

Figure 7 shows the results of treatment of the experimental data (Figs. 4 and 5) for large pulse lengths,

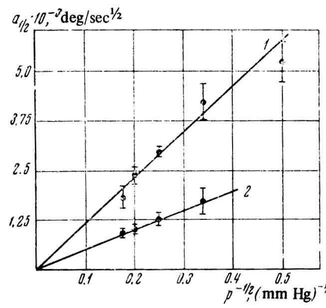

FIG. 6. Dependence of the coefficient $a_{1/2}$ on the reduced pressure (density) of helium for different currents: 1 – i = 2.3 A, $a_{1/2}\sqrt{p} = (11.6 \pm 1.8) \times 10^3$ deg-sec$^{-1/2}$ (mm Hg)$^{1/2}$; 2 – i = 1 A, $a_{1/2}\sqrt{p} = (5.2 \pm 1) \times 10^3$ deg-sec$^{-1/2}$ – (mm Hg)$^{1/2}$.

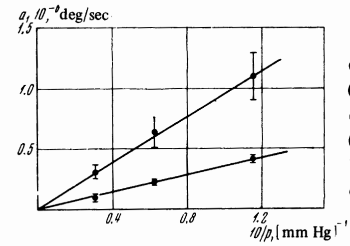

FIG. 7. Dependence of the coefficient a_1 on the reduced pressure (density) of helium for different currents: 1 – i = 2.3 A, $a_1 p = (9.5 \pm 2) \times 10^6$ deg-sec^{-1} –mm Hg; 2 – i = 1 A, $a_1 p = (3.6 \pm 0.2) \times 10^6$ deg-sec^{-1} –mm Hg.

when the heating of the gas is proportional to τ. The coefficient a_1, as is seen from Fig. 7, is inversely proportional to the density and is directly proportional to the current, as is $a_{1/2}$. For each value of the current, the product $a_1 p$ is seen to be a constant; it is equal to $(9.5 \pm 2) \times 10^6$ deg-sec^{-1}-(mm Hg) for a current of 2.3 A and $(3.6 \pm 0.2) \times 10^6$ for a current of 1 A. The ratio of these quantities amounted to 2.6 ± 0.5 and agrees with the ratio of currents within the limits of scatter.

The linear dependence of the gas temperature on the pulse length, current and reciprocal of the pressure is in agreement with the calculation for the other limiting case, in which the electron density reaches saturation because of ambipolar diffusion. In this case the coefficient a_1 must be compared with Eq. (4.13), according to which

$$a_1 = \frac{j}{Nek}\left(\frac{m\varepsilon_0}{2\tau_{ea}}\frac{D_a}{\Lambda^2}\right)^{1/2} \infty\, ip^{-1}. \tag{5.4}$$

The ambipolar diffusion coefficient D_a can be estimated directly from the experimental values of a_1 and $a_{1/2}$. To be precise,

$$D_a p = 2\Lambda^2 (a_1 p \,/\, a_{1/2}\sqrt{p})^2. \tag{5.5}$$

From the data for a current i = 2.3 A, we obtain the value $D_a p = (5.4 \pm 1.5) \times 10^5$ cm^2-sec^{-1}-mm Hg, and from the data for i = 1 A, we get $D_a p = (3.9 \pm 1.2) \times 10^5$ cm^2-sec^{-1}-mm Hg.

The theoretical expression for the ambipolar diffusion coefficient has the form

$$D_a = \frac{kT_e}{e}\mu_+ = \frac{kT_e}{MN\langle Q_{ia}v_i\rangle}, \tag{5.6}$$

where $\mu_+ = e\tau_+/M$ is the mobility of the atomic ions; $1/\tau_+ = N\langle Q_{ia}v_i\rangle$ is the frequency and Q_{ia} is the collision cross section of ions with atoms. This cross section is determined fundamentally by the process of the charge exchange of ions on atoms. According to the experimental data given in[7], the charge exchange cross section Q_{ia} depends logarithmically on the gas temperature and at low temperatures has the limiting value Q_{ia}

$\approx 3 \times 10^{-15}$ cm^2. Replacing Q_{ia} by this maximum value and substituting in (5.6) $\langle v_i \rangle = (16kT/\pi M)^{1/2}$, we get

$$D_a p = 2.2 \cdot 10^5 T_e / \sqrt{T} [\text{cm}^2 \text{ sec}^{-1}\text{-mm Hg}], \qquad (5.7)$$

where T_e is expressed in eV, and T in °K. If we take $T_e \approx 5$ eV, and the gas temperature $T \sim 10°$K, then we get $D_a p \sim 3.5 \times 10^5$ cm^2-sec^{-1}-mm Hg—in excellent agreement with the experimental values from (5.5). It is difficult to claim better agreement of calculation and experiment, inasmuch as the calculation was based on a rather rough model (introduction of the parameter ϵ_0, lack of account of losses of energy by radiation, neglect of the dependence of D_a on T, and so forth).

The value of D_a can also be estimated independently—from the time at which the curves of Figs. 4 and 5 enter into straight line dependence of the temperature T on τ. The values of $D_a = \Lambda^2/\tau_0$ and $D_a p$ are given in the table,

p, mm Hg	τ_0, μ sec	$D_a \cdot 10^{-4}$, cm^2-sec^{-1}	$D_a p \cdot 10^{-5}$, cm^2-sec^{-1}-mm Hg	p, mm Hg	τ_0, μ sec	$D_a \cdot 10^{-4}$, cm^2-sec^{-1}	$D_a p \cdot 10^{-5}$, cm^2-sec^{-1}-mm Hg
8.7	7÷8	5.7÷5	5÷4.4	25	25÷30	1.6÷1.3	4÷3.3
16	15÷18	2.7÷2	4.3÷3.2	33	32÷37	1.3÷1.1	4.4÷3.7

taken from the condition that the time at which the straight line dependence of T on τ takes over is equal to $\tau_0 = \Lambda^2/D_a$. It is seen that this independent estimate is also in excellent agreement with the results of measurement and calculation given above.

Elementary calculation of the electron density from Eq. (4.12) with the use of the experimental coefficients $a_{1/2}$ and a_1 permit us to determine the degree of ionization of the helium plasma in the steady state ($\tau > \Lambda^2/D_a$):

$$\frac{n_0}{N} = \frac{k}{2\varepsilon_0} \frac{a_{1/2}^2}{a_1} = \begin{cases} 6.2 \cdot 10^{-6}, & i = 2.3\text{A} \\ 3.2 \cdot 10^{-6}, & i = 1\text{A} \end{cases}. \qquad (5.8)$$

The limiting value of the electron concentration should be proportional to the gas density and to the current. For example, for a current of 2.3 A and p = 10 mm Hg, $N = 3.56 \times 10^{17}$ cm^{-3}) the quantity $n_0 = 2.2 \times 10^{12}$ cm^{-3}. Such a value of electron concentration has a reasonable order of magnitude and is in agreement with the results of direct measurements carried out by us quite recently by a microwave method.

Summing up, it should first be noted that the whole set of experimental results confirm the validity of our interpretation of the low-frequency oscillations of the radiation of helium plasma as the phenomenon of acoustic oscillations. Measurement of the periods of oscillation makes it possible to determine the temperature of the atoms directly in a non-isothermal plasma for a high-frequency pulse discharge. The elementary calculation carried out in the present work of the kinetics of pulsed heating of a plasma is shown to be in excellent qualitative and, in a number of cases, in quantitative, agreement with experiment. On the basis of analysis of the oscillations, one can determine the rough parameters of the plasma, such as heating of the gas, electron concentration and also the ambipolar diffusion, averaged collision cross section, etc. Thus the study of the oscillations of the intensity is a convenient experimental method for the diagnostics of plasma at low temperatures.

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175