Supercooled quasistationary beam plasma of decreased temperature

E. N. Snezhkin and M. V. Nezlin

I. V. Kurchatov Institute of Atomic Energy
(Submitted April 6, 1977)
Zh. Eksp. Teor. Fiz. 73, 913–922 (September 1977)

The conditions for the production of a deeply supercooled quasistationary plasma by an intense electron beam in a dense gas are considered. The paper consists of two parts, experimental and theoretical, and is a direct continuation of the first experiments [S. V. Antipov *et al.*, Sov. Phys. JETP **38**, 931, (1974)] on the production of a supercooled plasma with a beam. The principal method of lowering the electron temperature T_e of a helium plasma, just as in the earlier study, involves addition of molecular hydrogen. Optimization of the experimental conditions has made it possible to decrease T_e by a factor 2–3 compared with the earlier work. Under the new condition, at a helium-hydrogen mixture density (2–8) $\times 10^{18}$ cm^{-3}, the electron temperature is $T_e \lesssim 0.2$ eV and their concentration is $N_e \gtrsim 1\times 10^{14}$ cm^{-3}. A medium with these parameters is in a high state of disequilibrium. Thus, the plasma density exceeds the thermodynamic-equilibrium value (determined by the Saha formula) by approximately 20 orders of magnitude (!). The corresponding excess of the concentration of the excited helium atoms is even larger. Such a medium is of interest for applications connected with the properties of excited atoms and molecules and with kinetics of recombination. The presented calculations of the plasma parameters (N_e and T_e) agree with the experimental data.

PACS numbers: 52.50.Dg, 52.25.Lp

INTRODUCTION

If a plasma is in thermodynamic equilibrium, then its parameters—the electron temperature T_e and the concentrations of the charged particles N_e and of the neutral atoms (mainly N_0 in the ground state and N^* in the excited states) are connected by the known Saha formula. In a nonequilibrium plasma, T_e can be either larger or smaller than in an equilibrium plasma with given N_0 and N_e; in the former case the plasma is called superheated, and in the latter supercooled. By comparison with the thermodynamic-equilibrium plasma, a supercooled plasma with a given T_e is characterized by increased values of N_e and N^*. This excess can reach many order of magnitude—for example 12 orders in the electron density and seventeen(!) in the density of the excited atoms, as was the case in the preceding experiments,[1] in which a quasi-stationary supercooled plasma was obtained for the first time (helium-hydrogen, $T_e \approx 0.3$–0.4 eV, $N_e \approx (2-3)\times 10^{15}$ cm^{-3}, $N_0 \approx (1-2)\times 10^{18}$ cm^{-3}). Under the conditions of the present study, the deviations of the concentrations of the electrons and of the exited atoms from their equilibrium values is even larger. To produce a quasistationary supercooled plasma, we used an electron beam with electron energy ~ 10 keV and current density 10 – 100 a/cm^2. The fast beam particles produce ionization, and the plasma is predominantly recombining. In the case of a dense plasma consisting of atomic ions, the main type of recombination is of the three-particle impact-radiation type.[2,3]

Continuing the investigations initiated in[1], we have optimized the experimental conditions for plasma production by improving the system of gas supply to the working volume, by choosing optimal concentrations of the atoms of the working gas (helium) and of the cooling admixture (hydrogen) as well as the parameters of the electron beam. This provided a dependable quasistationary supercooled "beam" plasma with a minimum possible (at the given electron density $N_e > 10^{14}$ cm^{-3}) electron temperature: $(T_e)_{\min} \lesssim 0.2$ eV. The importance of this decrease of T_e is demonstrated already by the fact that the degree of supercooling of a "beam" plasma increases like $\exp(I/T_e)$, where I is the ionization energy of the gas atom (in our case of helium gas, $I = 24.5$ eV).

A quasistationary supercooled plasma, being a medium with anomalously high concentration of the excited atoms, can be of considerable interest for plasma chemistry, since the effective cross section for the collisions of the excited atoms is proportional to n^4 (n is the principal quantum number), and the rate of the fusion reactions in triple collisions is even proportional to n^{10} (see[4]). This medium is of interest also for applications in which the recombination kinetics is significant.[2,3]

It was shown earlier[1] that the only effective method of producing a quasistationary supercooled plasma is the beam method. A plasma with a beam, however, is known[5,6] to be quite prone to the excitation of collective (wave) degrees of freedom, which leads to a strong heating of the plasma particles. It is therefore easiest to obtain with an electron beam a hot plasma ($T_e \gg I$), more difficult to obtain a low-temperature plasma ($T_e \lesssim I$), and particularly difficult to obtain a supercooled plasma ($T_e \ll I$), for example one with $T_e \lesssim 10^{-2} I$, as in the present study. In the latter case it is absolutely essential to nip in the bud all traces of any plasma (two-stream) instability, by choosing a collisional plasma regime and the appropriate boundary conditions.[1,4,5] An additional obstacle to the production of a dense supercooled plasma is that the coefficient of three-particle recombination increases like

 0038-5646/77/4603-0481$02.40

$T^{-9/2}$ with decreasing temperature.[2,3]

Taking the foregoing into account, it is easily seen that the present study, in which we were able to decrease T_e by a factor 2–3 compared with the previously[1] attained level, has a tangible physical meaning and is of practical significance.

1. EXPERIMENTAL DATA

All the experiments described here were performed on the same experimental setup and with the same diagnostic means as in the preceding study[1]; the installation is described in Fig. 1 and its caption. To optimize the plasma regime (and primarily do decrease appreciably the electron temperature), the following modifications to the installation (Fig. 1) were made:

1. The system for supplying the working gases (helium, hydrogen) into the volume ahead of the valves, from which they were fed to the working volume during the shot (i. e., when the pulsed valve was opened), was reconstructed to increase the pressure in the volume ahead of the valve to 5 atm. This 10-liter volume was first evacuated to 1×10^{-3} mm Hg, and the gases were fed to it directly from high-pressure flasks. The pressure of the working-gas mixture in the working volume was determined by a number of factors: the pressure in the volume ahead of the valves, the valve control voltage, the delay of the beam pulse relative to the instant of the opening of the valve. The maximum amount of gas fed to the working volume during the time of opening of the pulsed valve (up to 9 msec) was two liters at atmospheric pressure. The gas concentration in the working volume was then 1.2×10^{18} cm^{-3}, larger by almost one order of magnitude than previously,[1] and this made it possible to lower substantially the electron temperature T_e (see below).

2. The new gas-supply system (Fig. 1) has made it possible to prepare a mixture of high-purity gases. According to the specifications, the extraneous impurities in the helium did not exceed 0.0055% (N_2—0.002%, Ne—0.002%, H_2O—0.0005%, O_2—0.0005% hydrocarbons—0.005%), and those in hydrogen did not exceed 0.0036% (N_2—0.003%, O_2—0.005%, H_2O—0.001%, while the other impurities were practically nonexistent). A decrease in the number of extraneous impurities was needed in principle, for otherwise the charge exchange of the helium ions with the molecules of the indicated gases (which proceeds faster by four orders (!) than with hydrogen[7]) could decisively distort the properties of the medium (see Sec. 2 concerning the role of the charge-exchange process).

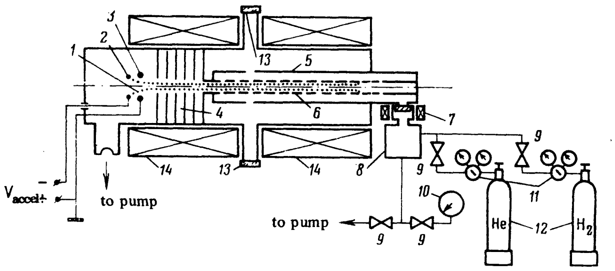

FIG. 1. Experimental setup: 1—electron beam, 2—annular cathode, 3—accelerating electrode, 4—gas delay line, 5—outer tube, 6—inner tube that limits the working volume, 7—electromagnetic valve, 8—volume ahead of valve, 9—valve, 10—manometer, 11—pressure reducer, 12—gas flasks, 13—windows for spectroscopic diagnostics, 14—magnetic-field coils.

3. To make the distribution of the working-gas pressure uniform over the axis of the electron beam, many openings were drilled in the tube in which the working volume was contained (3.2 cm dia, 100 cm length), and this tube was placed in an outer tube of 8 cm diameter. When the pulsed valve was opened, the gas first entered the outer tube and then—through the holes—in the inner tube. Since the total area of the holes in the inner tube was much larger than the cross-section area of the working volume and much less than the area of the cross section of the cylindrical volume between the tubes, the distribution of the gas pressure along the axis of the inner tube could rapidly become equalized.

In all the experiments, the energy of the beam electrons was 10–20 keV, the beam current was usually 8–15 *a*, and the intensity of the external longitudinal magnetic field in the working volume was 1200 Oe, and the beam diameter was ≈ 1 cm. The beam pulse duration (several hundred microseconds) was determined by the breakdown that occurred in the electron beam under the influence of the incoming plasma, and depended on the condition of admission of the working gases, i. e., on the pressure in the volume ahead of the valves, and the valve-control voltage, and on the delay between the turning-on of the beam and the opening of the valve.

The electron-gun cathode was a ring of 2.2 cm diameter (made of tungsten wire of 1.2 mm diameter). The gun was located outside the solenoid, in a region where the magnetic-field intensity was about one-fifth the intensity in the working volume. The gun produced a converging electron beam that diverged again after leaving the working volume. The plasma-pinch diameter in the working volume was about 1 cm.

The plasma parameters (averaged over the plasma-pinch parameter at the center of the setup) was measured with a time resolution.[1] The plasma concentration was determined from the Stark broadening of the H_β line of the Balmer series of hydrogen, and the electron temperature was determined from the relative intensities of the lines of this series.[1] The experimental results are shown in Figs. 2 and 3. The parameter of the family of the curves is the helium/hydrogen ratio in the mixture N_{He}/N_{H_2} (N_{He} and N_{H_2} are the concentrations of the helium atoms and the hydrogen molecules). Under the conditions of Figs. 2 and 3, the frequency of the ionization of the gas by the mean, with allowance for the contribution of the secondary electrons, is $\nu_i = N_1\langle\sigma v\rangle_i \approx 100-200$ sec^{-1}, where N_1 is the beam-electron density. These results yield a different electron temperature than those obtained earlier[1] (at the same mixture proportion): the decrease of T_e is due to the increase of the concentration of the "cooling" hydrogen impurity (see the comments concerning Fig. 4b below).

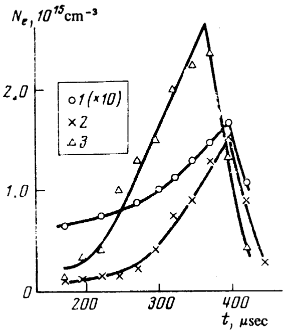

FIG. 2. Time dependence of the plasma density at various H_2 contents in the helium-hydrogen mixture (experiment. 1—$N_{H_2}=N_{He}$, 2—$N_{H_2}=\frac{1}{2}N_{He}$, 3—$N_{H_2}=\frac{1}{9}N_{He}$. $N_{He}=(2-4)\cdot 10^{18}$ cm^{-3} and $\nu_i\approx 100-200$ sec^{-1} everywhere. The time is measured from the instant of turning on the electron beam, and the instant when the beam is stopped corresponds to the maximum density.

Because T_e is low, the plasma density also turns out to be smaller than in[1]: in the recombination regime of the plasma, the maximum possible N_e is proportional to $T_e^{3/2}$. Nonetheless, as is seen directly from a comparison of the conditions of the present experiments and the preceding ones[1] (mainly from the values of T_e), under the conditions of Fig. 2 the plasma density exceeds the thermodynamic-equilibrium value N_e determined by the Saha formula for $T_e=0.2$ eV (see relation (1) of[1]) by approximately twenty orders of magnitude (!) Such a repopulation of the ionization continuum is quite typical of a supercooled plasma, all the more so in helium, where $\exp(I/T_e)$ is particularly large.

2. CALCULATION OF THE ELECTRON DENSITY AND TEMPERATURE IN A SUPERCOOLED PLASMA

To calculate the parameters of the investigated plasma we start from the following premises.

1. The plasma electrons have a Maxwellian energy distribution with a temperature T_e.

2. The gas of the heavy particles (charged and neutral) serves as a thermostat with temperature T (see [1]). A value $T=0.1$ eV is assumed in all the calculations. This assumption is based on an elementary calculation that shows that an electron beam with energy 10–20 keV and current density 5–10 a/cm^2 manages to heat, during the characteristic time of the beam pulse (~200 μsec—Figs. 2 and 3) a helium-hydrogen mixture (in a ratio 1:1) to an approximate temperature $T\approx 0.1$ eV (with allowance for the small thermal expansion of the heated gas).

3. The contribution of the secondary electrons to the ionization of the He atoms manifests itself in an effective increase of the ionization frequency ν_i by a factor of approximately 1.5.[8a] We assumed in the calculations $\nu_i=200$ sec^{-1}, which corresponds to an electron beam energy 10–20 keV and a current density 10–15 a/cm^2 (the calculation results do not change significantly if it is assumed that $\nu_i=100$ sec^{-1}—see below).

Consider the balance of the He^+ ions in a plasma in a stationary state. These ions are produced only when the beam ionizes the He atoms, at an ionization frequency ν_i, and are annihilated via the following three channels:

1. Three-particle (impact-radiative) recombination:

$$He^++e+e \xrightarrow{3} He+e+E_{kin}, \quad (1)$$

where E_{kin} is the electron kinetic energy. For the coefficient of the rate of this recombination we assume the well-known expression[3]

$$\beta=3\cdot 10^{-27}\,T_e^{-9/2}\ \text{cm}^6/\text{sec}$$

where T_e is in eV.

2. Charge exchange with the H_2 molecules:

$$He^++H_2 \xrightarrow{k_2} \begin{cases} H^++He+H, \\ H_2^++He \\ HeH^++H. \end{cases} \quad (2)$$

At $T=0.1$, this reaction has a rate constant $k_2\approx 1.5\times 10^{-13}$ cm^3/sec.[7a]

3. Conversion into a molecular He_2^+ ion:

$$He^++2He \xrightarrow{k_3} He_2^++He. \quad (3)$$

At $T=0.1$ eV this conversion rate constant is $k_3\approx 4\times 10^{-32}$ cm^6/sec.[9a]

The balance equation of the He^+ ions is thus

$$\nu_i N_{He}=\beta N_{He^+}N_e^2+k_2N_{He^+}N_{H_2}+k_3N_{He^+}N_{He}^2. \quad (4)$$

We shall show now that the He^+ ions can be regarded with high accuracy as the only ions in the plasma $N_{He^+}\approx N_e$, i.e., that the other ions produced as a result of the charge exchange (2) and conversion (3) vanish so rapidly that their concentrations are negligibly small in comparison with the concentration of the He^+ ions. To this end, we take into consideration the following processes:

All the ions that are produced in the charge exchange (2) of the helium ions with the hydrogen molecules are

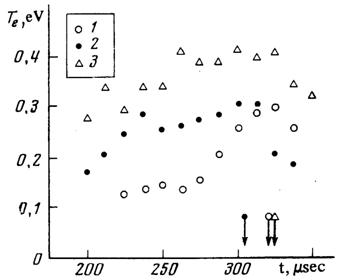

FIG. 3. Time dependence of the plasma-electron temperature at various H_2 contents in the helium-hydrogen mixture (experiment). 1—$N_{H_2}=N_{He}$, 2—$N_{H_2}=\frac{1}{3}N_{He}$, 3—$N_{H_2}=\frac{1}{9}N_{He}$. $N_{He}=(2-4)\cdot 10^{18}$ cm^{-3} and $\nu_i\approx 100-200$ sec^{-1} everywhere. The time is reckoned from the instant when the electron beam is turned on, and the instants of the beam shutoff are marked by arrows.

converted, after collision with the H_2 molecules, into H_3^+ ions:

$$H^+ + 2H_2 \xrightarrow{k_a} H_3^+ + H_2, \tag{5a}$$

$$H_2^+ + H_2 \xrightarrow{k_b} H_3^+ + H, \tag{5b}$$

$$HeH^+ + H_2 \xrightarrow{k_c} H_3^+ + He. \tag{5c}$$

In the temperature range of interest to us, the measured rate constants of these reactions are approximately $k_a \approx 3\times10^{-29}$ cm^6/sec and $k_b \approx k_c \approx (2-3)\times10^{-9}$ cm^3/sec.[10]

The molecular ions He_2^+ produced as a result of the conversion (3) on the atomic ions also react with the hydrogen molecules:

$$He_2^+ + H_2 \xrightarrow{k_6} \begin{cases} H^+ + H + 2He, \\ H_2^+ + 2He, \\ HeH^+ + H + He, \\ He_2H^+ + H, \\ HeH_2^+ + He. \end{cases} \tag{6}$$

The combined rate constant of all channels (6), determined in experiment, is approximately $k_6 \approx 5\times10^{-10}$ cm^3/sec in the temperature range of interest to us.

The reaction of the complex molecular ions such as He_2H^+ and HeH_2^+ with H_2 again results in the same ion H_3^+ (the reaction rate constant is $k_r \approx 3\times10^{-10}$ cm/sec).

Comparison of the rates of the charge-exchange and conversion processes (2 and 3), on the one hand, with the reactions of hydrogen with the ionized products of the charge exchange and conversion, on the other, show that at $N_{He} \lesssim 10^{20}$ cm^{-3} and $N_{H2} \gtrsim 10^{17}$ cm^{-3} (i. e., certainly in the entire working region of the helium-hydrogen mixture parameters of interest to us) the characteristic time of the annihilation of the He^+ ion via conversion and charge exchange is much larger than the average time of the subsequent conversion of the produced ions into H_3^+ ions. But the H_3^+ ions experience very rapid (dissociative recombination[12]:

$$H_3^+ + e \xrightarrow{k_7} H_2 + H, \tag{7}$$

which is much faster than the (three-particle) recombination of the He^+ ions under our conditions. The coefficient of the recombination of the H_3^+ ion at $T = 0.1$ eV is $k_7 \approx 1.5\times10^{-7}$ cm^3/sec.[12] This means that even when the number of H_3^+ and He^+ ions produced per unit time is the same, the ratio of their concentrations in the stationary state, $N_{H_3^+}/N_{He^+} = \beta N_e/k_7$, is less than 10^{-2} under the conditions of our experiments. It can therefore be assumed that the He^+ ions that participate in the charge exchange and in the conversion are practically instantaneously converted into neutral atoms and molecules in the time scale of our problem. This means that, first, charge exchange and conversion decrease the plasma density appreciably, and second, the densities of all the ions except He^+ can be neglected.

It should be noted that there exists one more channel of H_2^+ ion annihilation, namely dissociative recombination:

$$He_2^+ + e \xrightarrow{k_8} He + He, \tag{8}$$

with a rate constant that patently does not exceed $k_8 \lesssim 1.7\times10^{-8}$ cm^3/sec.[9b] Comparing also the (apparently greatly overestimated) value of the constant k_8 with the rate constant of the reactions (6), we arrive at the conclusion that at $N_e < 3\times10^{-2} N_{H_2}$ (i. e., certainly in the entire working region of the parameters of the medium), the dissociative recombination (8) can be disregarded as a channel for the vanishing of the He_2^+ ions.

It is easily seen (by comparing the constants of processes (8) and (6)) that if dissociative recombination were the main channel of the vanishing of the molecular ions He_2^+ (as would be the case in the absence of molecular hydrogen), then the He_2^+ ions would be the predominant ions in the plasma. In the presence of a hydrogen admixture in the helium, however, the plasma consists mainly of He^+ atomic ions. This change in the ion composition in the helium plasma under the influence of a molecular-gas (argon) impurity was observed also in recent experiments by Korolev and Khuzeev[16] on the ionization of dense helium ($p = 1-5$ atm) by a relativistic electron beam.

Thus, we shall henceforth assume in (4) that $N_e = N_{He^+}$. To determine the self-consistent plasma parameters (n_e, T_e) we must supplement Eq. (4) with the heat-balance equation for the electrons. We obtain this equation by the following reasoning:

When helium is ionized by an electron beam, the average energy consumed in the production of one pair of ions is $W = 46$ eV,[8a] and the ionization energy losses amount to $W\nu_i N_{He}$ per cm^3 of gas per second. In three-particle recombination, all this energy goes to the electron gas. On the other hand, the rate at which energy is diverted from a unit volume of the electron gas to the heavy particles (to the thermostat) includes the following components that correspond to electron cooling in elastic collisions with helium ions and atoms and in inelastic collisions with excitation of the first vibrational level of the H_2 molecule:

$$\begin{aligned} Q_{el\ He} &= \frac{3m}{M}(T_e - T)N_e N_{He}\langle\sigma v_e\rangle_{el}, \\ Q_{el\ He^+} &= \frac{3m}{M}(T_e - T)N_e N_{He^+}\langle\sigma v_e\rangle_{Coul}, \\ Q_{vib\ H_2} &= E_{vib\ H_2} N_e N_{H_2}\langle\sigma v_e\rangle_{vib\ H_2}, \end{aligned} \tag{9}$$

where m and M are the masses of the electron and atom, T is the temperature of the heavy particles (ions and atoms—here and below expressed in electron volts).

For the rate constants of these processes we assume the following relations:

$$\langle\sigma v_e\rangle_{Coul} = 3\cdot10^{-6}\, T_e^{-3/2}\Lambda \ [13],$$

where $\Lambda = 23.1 - 0.5\ \ln(N_e/T_e^3)$ is the Coulomb logarithm,

$$\begin{aligned} \langle\sigma v_e\rangle_{el} &= 4\cdot10^{-8}\, T_e^{1/2}\ [14], \\ \langle\sigma v_e\rangle_{vib\ H_2} &= 1.4\cdot10^{-9}\, T_e^{1/2}\,(E_{vib\ H_2} + 2T_e)\exp(-E_{vib\ H_2}/T_e)\ [15], \end{aligned} \tag{10}$$

where $E_{\text{vib H}_2} = 0.513$ eV is the first quantum of the vibrational energy of the H_2 molecule; $\langle \sigma v_e \rangle$ is in cm^3/sec.

For the stationary state, if we neglect the ionization losses of the beam to the (impurity) hydrogen molecules, we obtain:

$$W \nu_i N_{\text{He}} = Q_{\text{el He}} + Q_{\text{el He}^+} + Q_{\text{vib H}_2}.$$

It follows from the foregoing relations that in the stationary state a lowering of the plasma electron temperature to a level $T_e < 0.3$ eV (at $T = 0.1$ eV) can be attained only by exciting the vibrational degrees of freedom of the H_2 molecule. This electron-cooling channel will henceforth be regarded as predominant and (to simplify the calculation) even the only one;

$$W \nu_i N_{\text{He}} \approx Q_{\text{vib H}_2}. \qquad (11)$$

The rate of outflow of heat from the electron gas via elastic collisions is readily seen to be smaller by at least one order of magnitude.

We now write down, on the basis of (11), (9), (4), and the equality $N_e = N_{\text{He}^+}$ a self-consistent system of equation for the sought plasma parameters:

$$\begin{aligned} \nu_i N_{\text{He}} &= 3 \cdot 10^{-27} T_e^{-9/2} N_e^3 \\ &+ k_2 N_e N_{\text{H}_2} + k_3 N_e N_{\text{He}}^2, \\ W \nu_i N_{\text{He}} &= 1.4 \cdot 10^{-9} E_{\text{vib H}_2} N_e N_{\text{H}_2} T_e^{1/2} \\ &\times (E_{\text{vib H}_2} + 2T_e) \exp(-E_{\text{vib H}_2}/T_e). \end{aligned} \qquad (12)$$

We call attention primarily to the fact that, as seen from (12), to obtain a sufficiently low value of T_e the amount of hydrogen added to the helium must not be too small. But this amount should likewise not be too large. In fact, even at a mixture ratio 1 : 1 the beam-electron losses to ionization of the H_2 molecules are 50% larger than to the He atoms.[8] These losses, which were not included by us in the left-hand side of (11), affect adversely the heat balance of the plasma, and slow down the rate at which T_e decreases when more hydrogen is added to the helium. For these reasons, we confine ourselves to those He-H_2 mixtures in which the hydrogen-impurity concentration does not exceed the concentration of the main gas (helium).

The results of a numerical solution of the system (12) are shown in Fig. 4 as plots of N_e and T_e against the helium concentration at three helium-hydrogen mixture ratios, 1 : 1, 2 : 1, and 4 : 1. With increasing N_{He}, the plasma density first increases slowly, but when a maximum amounting to several times 10^{14} cm^{-3} is reached it begins to decrease because the ions go off to charge exchange and conversion. The electron temperature first decreases with increasing N_{He}—owing to the increased density of the cooling hydrogen admixture at a given mixture proportion, as indeed follows from (11). However, after reaching a certain minimum T_e again increases—because of the decrease of N_e (due to charge exchange and conversion) and the ensuing decrease of heat transfer to the thermostat (relation (9)). Thus, charge exchange and conversion lead to an effect of fundamental importance—a lower bound on T_e.

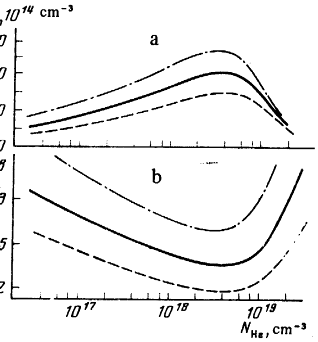

FIG. 4. Plasma density (a) and electron temperature (b) as a functions of the helium concentration at various H_2 contents in the helium-hydrogen mixture (calculation). (– – –) $N_{H_2} = N_{\text{He}}$, (——) $N_{H_2} = \frac{1}{2} N_{\text{He}}$, (–·–·–) $N_{H_2} = \frac{1}{4} N_{\text{He}}$. We put through-out $\nu_i = 200$ sec^{-1} and $T = 0.1$ eV.

3. DISCUSSION OF RESULTS

Proceeding to a comparison of the experimental data (Figs. 2 and 3) with the calculated ones (Fig. 4), we note the first the following main aspects:

1. The experimental and calculated values of N_e and T_e pertaining to the middle of the working region of the parameters of the investigated medium are practically equal.

2. When the hydrogen concentration is changed in either direction from the indicated range, the measured plasma density changes more strongly than the calculated one. This circumstance, in our opinion, can be easily attributed to the acceleration of the three-particle (impact-radiative) recombination, by quenching collisions of the excited helium atoms with the hydrogen molecules,[2] so that the helium goes over to the ground state, and the hydrogen molecule is ionized.[9c,d]

3. In accordance with the calculation (see relation (12)), the measured values of the electron temperature (Fig. 3) are substantially decreased when the percentage of the hydrogen in the helium is increased.

4. The peculiarities of the time dependence of N_e (Fig. 3) are due both to the change of T_e (N_e increases with increasing T_e in accordance with (4), since $\beta \propto T_e^{-9/2}$), and to the character of the current oscillogram of the electron beam.[1] In particular, the appreciable increase of N_e towards the end of the beam pulse is due to the increase of the beam current under the influence of the plasma that flows from the working volume into the region of the electron gun.

5. The assumption that the heavy-particle gas acts as a thermostat with a temperature $T \approx 0.1$ eV is justified by the existence of the conditions with very low tron temperature, $T_e \lesssim 0.2$ eV (Fig. 3).[1)]

6. The characteristic time of variation of the plasma parameters (N_e, T_e is of the order of 100 μsec (Figs. 2 and 3). It is much longer than the characteristic plasma-recombination time ($\tau_{rec} = 1/N_e^2$), which under the conditions of Figs. 2 and 3 varies in the range 1–10 μsec. Therefore the plasma (according to the terminology used by us) is quasistationarily recombining.

Taking into account the foregoing circumstances, we arrive at the conclusion that the experimental plasma parameters obtained in this study (N_e, T_e–Figs. 2 and 3) agree well with the calculations presented here (Fig. 4).

In conclusion, we emphasize once more that the ion-molecular reactions considered above, with participation of hydrogen molecules, exert a fundamental influence on the balance of the charged particles in a helium-hydrogen plasma. They lead not only to a decrease of the total density of the ions, but also to a decrease of the plasma composition: in the presence of a hydrogen admixture, the predominant ions in the plasma are not the molecular He_2^+ but the atomic He^+. Thus, calculations of the parameters of a supercooled helium plasma with a molecular admixture can agree with reality only if they take into account the ion-molecular reactions considered above, in particular the processes (2) and (6) of charge exchange of atomic and molecular helium atoms. These processes, however, were not taken into account in the theoretical paper.[17]

The authors are deeply grateful to A. S. Trubnikov and S. V. Antipov for great help with the experiments.

[1)]Under the considered experimental conditions the gas has no time to become superheated, so that dissociative thermal conductivity[1] plays no role at the indicated lowered temperatures.

[1]S. V. Antipov, M. V. Nezlin, E. N. Snezhkin, and A. S. Trubnikov, Zh. Eksp. Teor. Fiz. **65**, 1866 (1973) [Sov. Phys Phys. JETP **38**, 931 (1974)].

[2]L. M. Biberman, V. S. Vorob'ev, and I. T. Yakubov, Usp. Fiz. Nauk **107**, 353 (1972) [Sov. Phys. Usp. **15**, 375 (1973)].

[3]A. V. Gurevich and L. P. Pitaevskiĭ, Zh. Eksp. Teor. Fiz. **46**, 1281 (1964) [Sov. Phys. JETP **19**, 870 (1964)].

[4]A. A. Ivanov, Fiz. Plazmy **1**, 147 (1975) [Sov. J. Plasma Phys. **1**, 78 (1975)].

[5]Ya. B. Faĭnberg, At Energ. **11**, 313 (1961).

[6]M. V. Nezlin, Usp. Fiz. Nauk **102**, 105 (1970) [Sov. Phys. Usp. **13**, 608 (1971)].

[7]a) R. Johnsen and M. A. Biondi, J. Chem. Phys. **61**, 2112 (1974); b) F. C. Fehsenfeld, A. L. Schmeltekopf, P. D. Goldan, H. I. Schiff, and E. E. Ferguson, J. Chem. **44**, 4087 (1966); R. Johnson, M. T. Leu, and M. A. Biondi, Phys. Rev. A **8**, 1808 (1973); J. B. Laudenslager, W. T. Huntress, Jr., and M. T. Bowers, J. Chem. Phys. **61**, 4600 (1974).

[8]a) G. D. Alkhazov, Zh. Tekh. Fiz. **41**, 2513 (1971) [Sov. Phys. Tekh. Phys. **16**, 1995 (1972)]; b) M. Inokuti, Radiat. Res. **64**, 6 (1975); L. J. Kieffer and Gordon H. Dunn, Rev. Mod. Phys. **38**, 1 (1966).

[9]B. M. Smirnov, Iony i vozbyzhdennye atomy v plazme (Ions and Excited Atoms in Plasma), Atomizdat, 1974): a) p. 231; b) p. 293; c) p. 394; d) p. 397.

[10]L. P. Theard and W. T. Huntress, Jr., J. Chem. Phys. **60**, 2840 (1974).

[11]N. G. Adams, D. K. Bohme, and E. E. Fergusson, J. Chem. Phys. **52**, 5101 (1970).

[12]M. T. Leu, M. A. Biondi, and R. Johnsen, Phys. Rev. A **8**, 413 (1973).

[13]S. I. Braginzkiĭ, in: Voprosy teorii plazmy (Problems of Plasma Theory), ed. M. A. Leontovich, Atomizdat, Vol. 1, 1963, p. 183; D. V. Sivukhin, *ibid.*, Vol. 4, 1964, p. 81.

[14]B. Bederson and L. J. Kieffer, Rev. Mod. Phys. **43**, 601 (1971).

[15]D. E. Golden, N. F. Lane, A. Temkin, and E. Gerjuoy, Rev. Mod. Phys. **43**, 642 (1971).

[16]Yu. D. Korolev and A. P. Khuzeev, Opt. Spektrosk. **42**, 452 (1977) [Opt. Spectrosc. (USSR) **42**, 254 (1977)].

[17]Yu. I. Sytsko and S. I. Yakovlenko, Kvantovaya Elektron. (Moscow) **2**, 657 (1975) [Sov. J. Quantum Electron. **5**, 364 (1975)].

Translated by J. G. Adashko