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KINETICS OF CHARGE-EXCHANGE INTERACTION OF DENSE FLOWS

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The nonlinear problem of charge exchange between an ion flow and neutral particles is considered. An exact solution of the equations of charge-exchange interaction in plane geometry is found. Parameters determining the effectiveness of interpenetration of dense flows and the structure of the layer of intense interaction are obtained.

Introduction. The charge-exchange process is one of the main mechanisms of excitation of ions along with electron impact excitation and recombination. The quasiresonance character of the process makes it possible to produce inversion of the population of levels of highly-charged ions during charge exchange with atoms, molecules, or low-charged ions [1]. Thus, in the reactions $C^{+6} + H^0 \longrightarrow C^{+5} + H^+$ [2] or $O^{+6} + H^0 \longrightarrow O^{+5} + H^+$ [3], the trapped electron falls with probability higher than 90% on the shell with main quantum number $n = 4$. At high reagent concentrations (greater than 10^{16} cm^{-3}), the intensity of charge-exchange pumping of the indicated ions makes it possible to obtain large coefficients of radiation amplification in the ultraviolet vacuum (UVV) and x-ray spectral regions at a wavelength of 18.2 nm for the first reaction and at 52 nm for the second. At present, charge exchange as an elementary process has been thoroughly studied for many reactions. Exact information on the cross sections of particular channels of electron capture can be obtained experimentally, and for unexplored reactions, the developed theoretical models predict these cross sections fairly accurately.

However, the kinetics of charge-exchange interaction of flows has not been studied, in particular in a strongly linear regime with charge-exchange length smaller than the characteristic gas-dynamic scales. The problem is to determine the dynamics and properties of the region of intense interpenetration of flows (usually, a flow of highly charged ions moving through a medium of neutral particles). The only estimates were obtained by Bunkin et al. [4]. It was shown that the maximum effectiveness of mixing does not exceed 25% and is reached at half concentrations of the reagents, and the structure of the interaction region is determined not only by the structures of the fronts but also by the charge-exchange length. However, no quantitative parameters determining this structure and effectiveness of interpenetration was detected. As a result, a stringent limitation on the magnitude of permissible pumping was obtained, which made the present approach in the UVV-range unpromising. Later, the empirical limitations used turned out to be overestimated by several orders of magnitude. For example, the maximum ion flow that can effectively exchange charge with neutral particles $J_{\max} = n_i V_i = 3 \cdot 10^{18}$ cm$^{-2} \cdot$ sec^{-1} [4] is three orders of magnitude smaller than the one obtained in [5] $J_{\exp} = n_i V_i = 3 \cdot 10^{21}$ cm$^{-2} \cdot$ sec^{-1}. The limitation on the charge-exchange length ($L_p/V_i > 10^{-7}$ sec), related to development of possible instabilities, was overestimated by two orders of magnitude. An understanding of the role of the parameters determining the effectiveness of charge-exchange mixing of dense flows and the structure of the intense interaction region is needed to perform experiments on laser generation in the UVV region by charge-exchange pumping [6] and to explain the fact that results of previous experiments [2] are much smaller than those predicted by theory.

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In the present work, we develop an analytical model for the charge-exchange interaction of flows and compare calculations with experimental data.

Model for Charge-Exchange Interaction of Flows. We consider a flow of ions of charge i and concentration $n_i(r,t)$, moving at constant velocity V_i through an immobile medium of neutral particles of concentration $n_a(r)$. In the kinetics of flow interaction, charge exchange is taken into account by the continuity equation

$$\frac{\partial n_i}{\partial t} + \operatorname{div}(n_i \boldsymbol{V}_i) = -n_a n_i \sigma_i V_i + n_a n_{i+1} \sigma_{i+1} V_{i+1}, \qquad \frac{\partial n_a}{\partial t} = -n_a \sum_i n_i \sigma_i V_i, \tag{1}$$

where σ_i is the cross section of the process. Equations (1) are written with allowance for cascade charge exchange for all sorts of ions of the given element. The system should be supplemented by an equation of motion.

To clarify the nature of the charge-exchange interaction, we ignore external forces and elastic and inelastic scattering of particles. The last approximation is quite justified since the charge-exchange cross sections for highly charged ions (in excess of 10^{-15} cm^2) are usually an order of magnitude larger than the dissipation gas-dynamic cross sections. Below, we consider charge exchange for just one initial ion component of charge i. We ignore the influence of the ion components of lower charge that are formed during flow interaction, assuming that their charge-exchange cross sections (σ_{i-1}, σ_{i-2}, etc.) are much smaller. This approximation is rather conditional since with change in the charge, the cross sections decrease by only a factor of 2 or 3. However, for the investigation of the nature of charge exchange for dense flows, this is of no significance. It is also assumed that the ions and atoms that enter into the charge-exchange process are primarily in the ground quantum state (for which the specified cross sections are valid), although the interaction gives rise to exited ions. This approximation is based on the fact that the radiation de-excitation times for highly charged ions are usually much shorter than the characteristic gas-dynamic times $\tau = \delta/V_i$ (δ the scale of nonuniformity of concentration). For example, in the experiment whose results are given below, the ratio of these times was less than 0.1.

Thus, the simplified equations of charge-exchange interaction have the form

$$\frac{\partial n_i}{\partial t} + \operatorname{div}(n_i \boldsymbol{V}_i) \equiv \frac{\partial n_a}{\partial t} \equiv -I_{i-1} = -n_a n_i \sigma_i V_i, \tag{2}$$

where I_{i-1} is the rate of formation of excited ions during charge exchange. Previously [7], Eq. (2) was solved for the weak interaction regime. The inertial dispersion of a spherically symmetric cloud of laser plasma in a rarefied homogeneous atmosphere of neutral particles is considered. In a zero approximation, there is the solution

$$n_i = n_i^0 \exp(-n_a^0 \sigma_i r), \qquad n_a = n_a^0,$$

where $n_i^0(r,t)$ and n_a^0 are the unperturbed concentrations of the reactants. In the next approximation, the following solution is obtained:

$$n_a(r) = n_a^0 \exp(-R_c^2/r^2), \qquad n_i = n_i^0 \exp\left(-\int^r n_a(r)\sigma_i \, dr\right). \tag{3}$$

Here $R_c = \sqrt{N_i^{\text{tot}} \sigma_i/(4\pi)}$ is the radius of complete charge exchange for neutral particles and N_i^{tot} is the total number of ions in the spherical flow. This solution is applicable if the charge exchange length for ions $L_p = (n_a^0 \sigma_i)^{-1}$ is much greater than R_c, i.e., the interaction is weak if on a characteristic length L_p, the total number of ions of the flow that pass through unit area is much smaller than σ_i^{-1}. Solution (3) was used in a diagnostic problem of determining the ion concentration from the light emission in particular lines excited during charge exchange [7]. For problems of generation of intense UVV radiation, it is necessary to solve Eqs. (2) for the strong interaction regime.

We consider the problem in one-dimensional geometry. There is a planar flow of ions with an arbitrary concentration profile and constant velocity which collides with a medium of neutral particles with an arbitrary

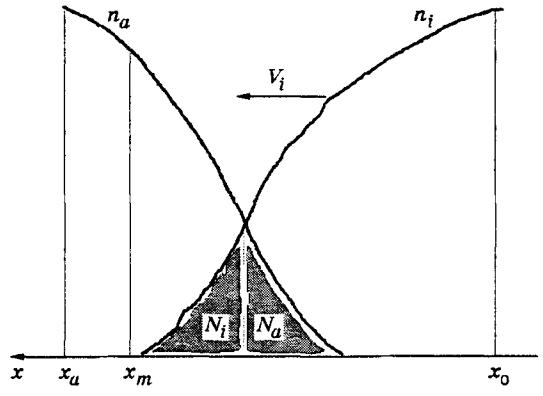

Fig. 1

density profile (Fig. 1). We introduce the integral ion flow $N_i = \int_{\infty}^{t} n_i(x,t)V_i\,dt$, which has the meaning of the total number of ions that have passed through unit area by moment t at the observation point x. This quantity can be written as the space integral $N_i = \int_{\infty}^{x} n_i(x,t)\,dx$ (integration is performed from a point located indefinitely far in the direction of the velocity vector). The ion concentration is expressed as $n_i = \partial N_i/\partial x$ or $n_i = \partial N_i/V_i\,\partial t$. Solving Eq. (2) for n_a, we obtain

$$n_a(x,t) = n_a^0(x)\exp(-N_i\sigma_i),$$

where $n_a^0(x)$ is the unperturbed concentration of neutral particles. Expressing n_i in (2) in terms of N_i, we obtain

$$\frac{\partial^2 N_i}{\partial t^2} + V_i\frac{\partial^2 N_i}{\partial x\,\partial t} = -n_a^0(x)\sigma_i V_i\frac{\partial N_i}{\partial t}\exp(-N_i\sigma_i).$$

Since in the selected coordinate system, the unperturbed concentration of neutral particles does not depend on time, the present equation is integrable:

$$\frac{\partial N_i}{\partial t} + V_i\frac{\partial N_i}{\partial x} = -n_a^0(x)V_i[1-\exp(-N_i\sigma_i)].$$

Introducing the coordinate $dX = V_i\,dt$ of an arbitrary moving plasma element, in the reference system of ions we have

$$\frac{\partial N_i}{\partial X} = -n_a^0(X)[1-\exp(-N_i\sigma_i)]. \tag{4}$$

In the reference system of ions, the unperturbed quantity N_i^0 is an integral of motion. Therefore, the integration constant is selected with the proviso that in the absence of interaction (cross section of the process or the concentration of neutral particles is equal to the zero point) $dN_i/dX = 0$. Integrating (4), we obtain $N_i\sigma_i = \ln[1+\exp(-N_a^0\sigma_i)(\exp(N_i^0\sigma_i)-1)]$, where $N_a^0 = \int_{-\infty}^{X} n_a^0\,dx$ is the total number of neutral particles (in unit area) on the path of motion of the selected plasma element to the point X. Hence we obtain the final expressions for the reactant concentrations at an arbitrary time and an arbitrary point in space:

$$n_a = n_a^0[1+\exp(-N_a^0\sigma_i)(\exp(N_i^0\sigma_i)-1)]^{-1},\quad n_i = n_i^0[1+\exp(-N_i^0\sigma_i)(\exp(N_a^0\sigma_i)-1)]^{-1}. \tag{5}$$

This solution can be found from simple physical arguments. Let at a certain point X, $N_i(X)$ ions pass through unit area before arrival of a selected plasma element. When the plasma element reaches the point $X+dX$, this number of ions is equal to $N_i(X+dX)$. According to the law of conservation of particles, a

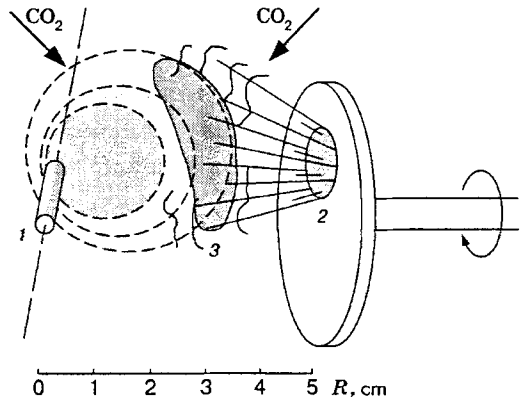

Fig. 2

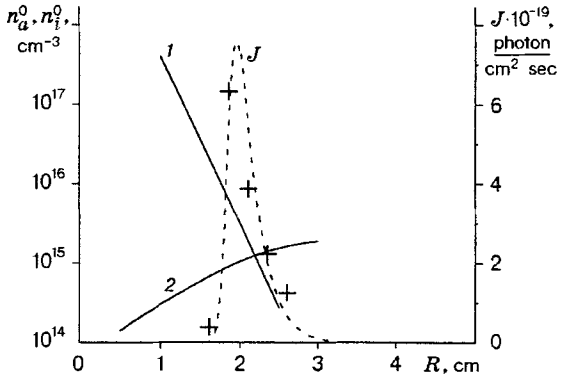

Fig. 3

decrease in the total number of ions on this path must be equal to the decrease in the number of neutral particles $dN_a = (n_a^0 - n_a)\,dX = -n_a^0(1 - \exp(N_i\sigma_i))\,dX$, which leads to Eq. (4).

For another geometry of the problem there is no analytical solution of Eqs. (2). However, these solutions in the form of partial differential equations can be reduced to a homogeneous differential equation of the first order, which is solved by numerical integration. Spherical geometry, which corresponds to experiments in which ions are produced by exposure of a flat target to laser radiation, is of greatest interest. The plasma flow can be considered as expanding self-similarly ($V_i = r/t$) from the point $r = 0$. In this case, instead of the integral flow through unit area, it is necessary to introduce the ion flow in unit solid angle, which in spherical geometry is an integral of motion: $N_i = r^2 \int^t n_i(r,t)V_i\,dt$. Then, the conservation law for particles leads to the equation

$$\frac{dN_i}{dR} = -n_a^0(R)R^2\Big[1 - \exp\Big(-\frac{N_i\sigma_i}{R^2}\Big)\Big], \tag{6}$$

where $R = V_i t$. Equation (6) is solved subject to the boundary conditions $N_i(R = 0) = N_i^0$. The concentration of neutral particles at the moment they pass through the selected plasma element is equal to $n_a(R) = n_a^0(R)\exp(-N_i\sigma_i/R^2)$. Since the ions move in a straight line, a solution can be obtained independently for any direction of dispersion for which the unperturbed distribution of reactant concentration is known.

The effectiveness of interpenetration (mixing of flows) is defined as the ratio of the product of the reactant concentrations attained during interaction to the product of the concentrations in the absence of interaction: $\eta = n_i n_a/(n_i^0 n_a^0)$. For solution (5), we have

$$\eta = \frac{\exp(-N_i^0\sigma_i + N_a^0\sigma_i)}{[1 + \exp(-N_i^0\sigma_i + N_a^0\sigma_i) - \exp(-N_i^0\sigma_i)]^2}. \tag{7}$$

From an experimental viewpoint, it is of interest to compare the actual permissible charge-exchange pumping intensity and the theoretical value calculated from the specified characteristic concentrations of reactants n_i^m and n_a^m in the initial unperturbed flows. The general effectiveness of interaction is defined as $\eta^* = (n_i n_a)_{\max}/(n_i^m n_a^m)$.

Comparison of the Analytical Solution with Experimental Results. The setting and results of experiments on charge exchange between a laser plasma flow and a compact gas cloud are described in detail in [5]. The geometry of the experiment is schematically shown in Fig. 2, where 1 is the gas target, 2 is the plasma target, 3 is the region of intense charge exchange between the flows, and R is the distance between the targets). The gas cloud was produced by CO_2-laser irradiation (duration 3 μsec, intensity 3 MW/cm^2) of a Caprolon $(C_6H_{11}ON)_n$ target in the form of a cylinder with diameter 0.5 cm and length 3 cm. After dispersion of the cloud with a front velocity of about $5 \cdot 10^5$ cm/sec for 4.5 μsec, the second CO_2 radiation beam (duration 100 nsec and intensity 1 GW/cm^2) produced a plasma flow on the second

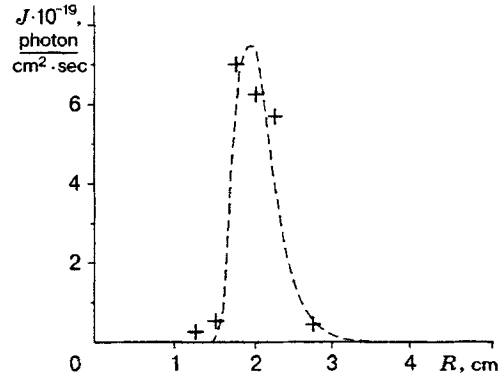

Fig. 4

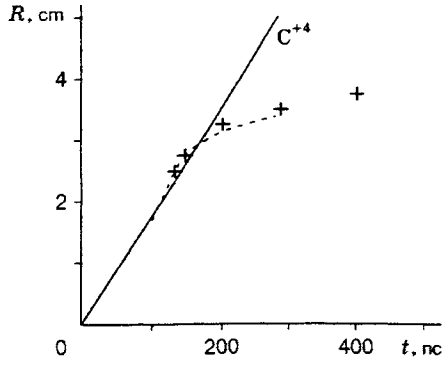

Fig. 5

flat target. This plasma flow dispersed in a cone with an angle of approximately 60° with a maximum velocity of $1.6 \cdot 10^7$ cm/sec and contained predominantly C^{+4} carbon ions at the front. The charge-exchange reaction between the indicated ions and the hydrogen atoms of the gas cloud results in the formation of C^{+3} ions excited at the 3p shell. This reaction is studied in detail in [3], where the cross section of the process $\sigma = 2.5 \cdot 10^{-15}$ cm^2. To determine the intensity of charge-exchange pumping of the 3p shell and, hence, the intensity of interaction, the light emission in the line 580.1 nm of the 3p–3s transition was measured. Since the forces of oscillators for lithium-like ions are known fairly exactly, it is possible to calculate the emission probability for the indicated transition during in one act of charge exchange. For plasma parameters in the interaction region $n_e \geqslant 4 \cdot 10^{15}$ cm^{-3} and $T_e < 10$ eV, we can assume that the 3s, 3p, and 3d subshells are mixed as a result of collisions and are populated according to their statistical weights because the frequency of the 3p–3d transitions due to the collisions is not lower than 10^{10} sec^{-1} and the rate of radiation de-excitation of the 3p subshell is $5 \cdot 10^9$ sec^{-1}. De-excitation of shell 3 occurs by radiation transitions to shell 2. In this case, the light-emission intensity in the line 580.1 nm is equal to the charge-exchange rate with a constant of proportionality $(6/18)A_{3p-3s}\tau_3 \approx 10^{-3}$, where $A_{3p-3s} = 3 \cdot 10^7$ sec^{-1} is the probability of 3p–3s transition and $\tau_3 \approx 10^{-10}$ sec is the total radiation lifetime of shell 3 summed up over the subshells. The concentration of C^{+3} ions in the excited 3p state is given by $n_{+3}(3p) = (6/18)\tau_3 n_a \sigma V n_{+4}$. The initial parameters of the C^{+4} ion flow were measured by the method of [7] from the light emission in the indicated line during plasma dispersion in a rarefied atmosphere of H_2. The light-emission intensity in the line was measured by an MDR monochromator with photoelectric recording. The entire spectral diagnostics system was previously calibrated for absolute measurements in the selected optical range. The concentration of the gas cloud was measured by a pressure piezoprobe [8].

Figure 3 gives the concentration distribution of the gas cloud n_a^0 (curve 1) with which the plasma interacted and the concentration n_i^0 of C^{+4} ions (curve 2) measured in the absence of the gas cloud at the time 200 nsec after the beginning of irradiation of the plasma target. Crosses show the spatial distribution of the light-emission intensity J in the line 580.1 nm of the C^{+3} ion, measured at the same instant for the case of plasma dispersion in the presence of the gas cloud. The dashed curve refers to the calculation using the model of charge-exchange interaction. The measurements were performed along the axis connecting the gas and plasma targets.

Figure 4 gives the distribution of the maximum (in time) intensity J of the indicated light emission, measured at various points (crosses are measurement results and the dashed curve is the calculation using the model). Figure 5 shows the $(R$–$t)$ diagram of motion of this maximum, i.e., the dynamics of penetration of the ion flow into the gas cloud (points are measurement results, the dashed curve is the calculation using the model, and the solid curve is the diagram of motion of the initial ions C^{+4} in the absence of the gas cloud). The center of the gas cloud is located at a distance $R = 5$ cm. It is obvious that intense interaction is concentrated in a narrow layer about 1 cm thick, which has distinct boundaries and is rapidly decelerated

as the plasma penetrates into the dense layers of the gas cloud. At the point of maximum interaction, where the concentration of neutral particles reached 10^{16} cm^{-3}, the charge-exchange length (less than 0.1 cm) was markedly smaller than the scale of heterogeneity of the gas cloud, which had an exponential profile with a characteristic length of about 0.22 cm.

The pumping and light-emission intensity in the line 580.1 nm were calculated by solving Eq. (6) in spherical geometry. The experimental quantities n_a^0 and n_i^0 are taken as unperturbed flow parameters. We note that allowance for the three-dimensional character of ion scattering does not introduce significant changes to the results obtained using formulas (5) since the thickness of the layer of intense interaction is markedly smaller than the distance from the plasma target to the layer. In Figs. 3–5, the calculation results are shown by dashed curves, and it is evident that they agree with the experimental results. Figure 5 demonstrates that the deceleration of the layer of intense interaction is completely explained within the framework of the charge-exchange model by the process of "depletion" of ions at the front and displacement of this layer into the depth of the flow. The effect of elastic scattering of ions on neutral particles is insignificant because of the much smaller atomic weight of the latter. The maximum charge-exchange pumping intensity was observed at $t \approx 200$ nsec at a distance of 3.25 cm from the plasma target (1.75 cm from the gas target), where the unperturbed values of the total number of neutral particles on the path of the plasma flow (in unit area) and the total number of ions that have passed through unit area are $N_i^0 = 10^{15}$ cm^{-2} and $N_a^0 = 2 \cdot 10^{15}$ cm^{-2}, respectively, and the values of unperturbed concentrations are $n_i^0 = 10^{15}$ cm^{-3} and $n_a^0 = 10^{16}$ cm^{-3}. From formula (7), it follows that the efficiency of interpenetration should be 7%. The experimental value is 10%. In (7), the sphericity of dispersion can be taken into account by evaluating N_a^0 from the formula $N_a^0 = \frac{1}{R^2}\int\limits_0^R n_a^0 r^2\, dr$. In this case, the calculation gives $\eta = 12\%$.

Discussion of Results. From the analytical solution obtained it follows that the effectiveness of interpenetration and the structure of the intense interaction layer are determined not by the local concentrations of the flows but by the integral quantities N_i^0 and N_a^0, which describe the flow pattern. A precise measure of the flow "density" is the reverse of the charge-exchange cross section. This criterion is also in agreement with the solution for the weak interaction regime (3). In the area of space considered, the medium is dense when the total number of particles in it (in unit area perpendicular to the direction of relative motion) is larger than $1/\sigma$. We consider the simple case of flows with a ledge-type structure (with infinitely steep front). At the moment the fronts collide, the effectiveness is equal to 100% since the values of N_i^0 and N_a^0 are approximately zero. However, with interpenetration of the flows on a combined length of charge exchange $(n_i + n_a)/(n_i n_a \sigma_i)$, the maximum effectiveness decreases to about 25%. Indeed, on this length, the values of $N_i^0\sigma_i$ and $N_a^0\sigma_i$ are approximately equal to 1. For large distances, the term $\exp(-N_i^0\sigma_i)$ in formula (7) can be ignored as compared to unity. As a result, we obtain

$$\eta = \frac{\exp(-N_i^0\sigma_i + N_a^0\sigma_i)}{[1 + \exp(-N_i^0\sigma_i + N_a^0\sigma_i)]^2} \leqslant 0.25.$$

Since the charge-exchange length for dense flows is much smaller than the length of the flows (or the actual attainable fronts), for most of the ions, charge exchange occurs with effectiveness of interpenetration not higher than 25%. The point of maximum intensity of interaction moves at a velocity that is lower than the velocity of relative motion of the flows by a factor of $n_i^0/(n_i^0 + n_a^0)$. The width of the mixing layer calculated at the half-height is $\Delta = L_p^* \ln((3 + \sqrt{8})/(3 - \sqrt{8})) \approx 3.5 L_p^*$, where $L_p^* = ((n_i^0 + n_a^0)\sigma_i^{-1}$ is the effective charge-exchange length. From the measurement data it follows that in the experiment, charge exchange between the ions and the neutral particles was achieved when the concentration of the latter was 10^{16} cm^{-3} and the effectiveness of interaction was close to the maximum. The considerable and abrupt deceleration of the maximum of charge-exchange pumping is explained by the fact that as the ion flow penetrates into the gas cloud, the number of neutral particles on the path of the ions increases exponentially and the maximum of the interaction is displaced into the depth of the flow.

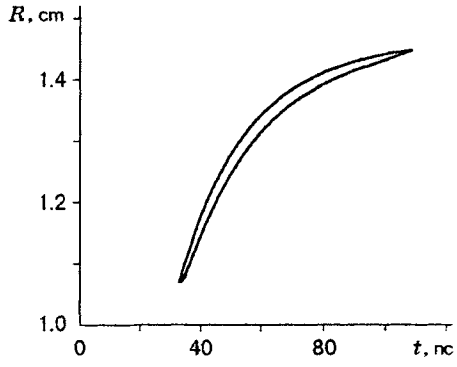

Fig. 6

We consider the interaction of flows having fronts of finite width (see Fig. 1). To simplify the analysis, we assume that the concentrations change exponentially from the specified shell $n_a^0 = n_a^m \exp((x - x_a)/l_a)$, $n_i^0 = n_i^m \exp(-(x - x_0)/l_i)$ with characteristic widths of the fronts l_a and l_i. The point $x_0 = V_i t$ moves with the ion-flow velocity, and the point x_a is stationary. The plasma flow is assumed to be limited by the point x_0. We have $N_a^0 = n_a^0 l_a$, $N_i^0 = N_{\text{tot}} n_i^0 / n_i^m$, where N_{tot} is the total number of ions in the plasma flow (in unit area). In view of the exponential dependence of the value of η on N_a^0 and N_i^0 for dense flows, the maximum charge-exchange rate (at a specified time) is at the point of maximum interpenetration, which, according to (4), is determined by the condition $N_a^0 = N_i^0$. For the coordinate of this point, we obtain the expression $x - x_0 = (x_a - x_0) l_i/(l_a + l_i) + (l_a l_i/(l_a + l_i)) \ln(N_{\text{tot}}/(n_a^m l_a))$. Hence it follows that the point of maximum charge-exchange rate can reach the required concentration of neutral particles n_a^m ($x_a < x_0$ provided that $x > x_0$) only if the total number of ions in the flow is greater than the number of neutral particles at the front: $N_{\text{tot}} < n_a^m l_a$. The physical meaning of this requirement is obvious: for the maximum concentration in the distribution of neutral particles to be reached, the ion flow should completely exchange charge to all neutral particles present at the front. Otherwise, ($N_{tot} < n_a^m l_a$) the point of maximum rate corresponds to the coordinate $x_m = x_a + l_a \ln(N_{\text{tot}}/(n_a^m l_a))$. The time dependence of the absolute value of this maximum is given by

$$I = n_i n_a \sigma_i V_i = \frac{n_i^m n_a^m \sigma_i V_i}{4} \frac{N_{\text{tot}}}{n_a^m l_a} \exp\Big(-2\frac{x_m - x_0}{l_i + l_a}\Big).$$

The time during which the maximum intensity of charge-exchange pumping is realized has characteristic value $\tau = (l_i + l_a)/(2V_i)$, i.e., it is of the order of the time of flight of a restricted ion flow. The rate of motion of the maximum is $V_m = V_i l_a/(l_i + l_a)$, and the characteristic width of the region in which the maximum intensity is observed is equal to the average length of the fronts: $\Delta x = (l_i + l_a)/2$. The characteristic width of the peak of maximum intensity at a particular time is given by the quantity $\Delta = 3.5/((n_a + n_i)\sigma_i) \approx 3.5 l_i l_a/(N_{\text{tot}} \sigma_i (l_i + l_a))$, which for dense flows ($N_{\text{tot}} \sigma_i \gg 1$) can be much smaller than the width of the entire region of maximum interaction Δx.

Thus, we obtain the following picture of the process. Intense charge exchange interaction of flows with fronts of finite width is concentrated in a narrow peak, which passes at velocity $V_m = V_i l_a/(l_i + l_a)$ over a region with dimension $\Delta x = (l_i + l_a)/2$ located near the layer of the gas front with concentration of neutral particles N_{tot}/l_a. The ratio of the width of the peak to the dimension of the intense-interaction region is determined by the "density" parameter of the ion flow $N_{\text{tot}}\sigma_i$. The general effectiveness of the interaction is $\eta^* = N_{\text{tot}}/(4 n_a^m l_a)$. Thus, to obtain maximum pumping, it is necessary to increase the reactant concentrations and to match the flow pattern, which is given by the condition $N_{\text{tot}}/(n_a^m l_a) \approx 1$.

The aforesaid is illustrated by an example of numerical modeling of an experiment on generation at a wavelength of 52 nm in the reaction $O^{+6} + H^0 \longrightarrow O^{+5} + H^+$ [6]. To increase the concentration and integral ion flow in the interaction region and obtain a high amplification coefficient for irradiation of the plasma

target, it is proposed to use a linear focus of length 2 cm and to decrease the distance between the targets to 3 cm (see Fig. 2). Figure 6 gives a diagram of motion of the layer (the region bounded by the curves) with a total amplification coefficient greater than 10 at a wavelength of 52 nm for two passes of radiation in the circuit of an opened resonator with one mirror. The plasma target is located at a distance $R = 0$, and the gas target is at $R = 3$ cm. As the induced laser radiation cross section we used the value $\sigma_{\text{ind}} = 4 \cdot 10^{-15}$ cm^2, which was calculated in [9], and the population of the upper laser level was evaluated by a procedure similar to the one employed above for the C^{+3} ion using the corresponding transition constants.

In previous experiments [2] on laser plasma dispersion in a homogeneous background gas with an atom concentration $n_a \geqslant 3 \cdot 10^{16}$ cm^{-3} and a total number of highly charged ions in unit solid angle $N_i^{\text{tot}} \approx 10^{14}$, the condition of matching of the flows $N_i^{\text{tot}}/(n_a l_a^3)$ on the experimental scale $l_a \approx 1$ cm was not satisfied, and charge exchange occurred at a neutral-particle concentration that was two or three orders of magnitude lower than the initial value. In the experiment of [5], the value of N_i^{tot} was about an order of magnitude higher, and l_a was an order of magnitude lower because of use of a compact gas cloud, which made it possible to considerably increase the effectiveness of interaction.

Conclusion. The obtained analytical solution of the problem of charge-exchange interaction of plane flows in a strongly nonlinear regime made it possible for the first time to establish the parameter that determines the effectiveness of interpenetration and the structure of the layer of intense interaction. This parameter depends not on the absolute concentrations of reactants at which interaction occurs but on the total number of ions (neutral particles) located at the fronts of the flows. Results of calculations using model the are in good agreement with the experimental data.

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