AMPLIFICATION OF VACUUM-ULTRAVIOLET RADIATION IN A DECAYING DENSE HELIUM PLASMA

L.I. Gudzenko, Yu.K. Zemtsov, and S.I. Yakovlenko
Nuclear Physics Research Institute of the Moscow State University
Submitted July 28, 1970
ZhETF Pis. Red. 12, No. 5, 244 - 248 (5 September 1970)

Interest in recombination of a dense plasma is connected, in particular, with the problem of developing short-wave quantum generators. Among the advantages of non-equilibrium recombination[1)] are the relative duration of the amplifying properties and the realizability of their repeated rapid restoration. A helium plasma is preferable at present not only from the point of view of theory (the cross sections of the elementary acts have been investigated in this case in relatively great detail), but also for experiment, since helium is an inert gas, and the wavelength intended for amplification (1641 Å) makes it possible to use mirrors and can be brought out from the resonator through solid windows.

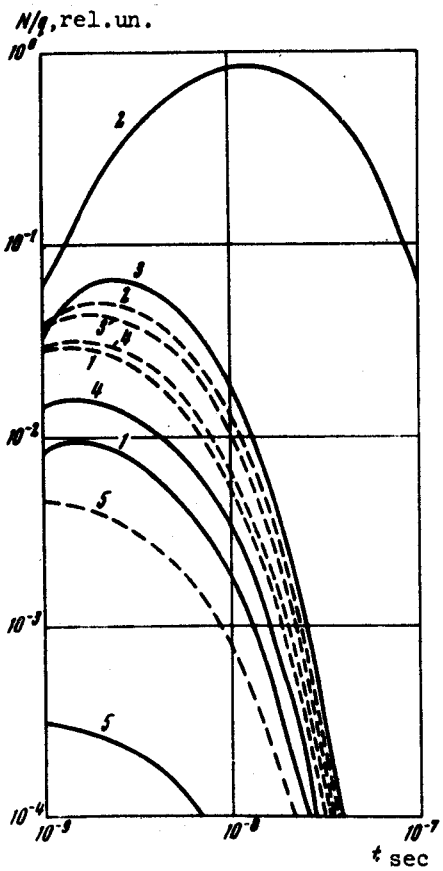

Fig. 1. Time dependence of the population of the He^+ levels n = 2 and n = 3 at $N_e = 10^{16}$ cm^{-3} and $T_e = 0.3$ eV, in relative units: 1 - without allowance for reabsorption, 2 - $N_0 = 0$, 3 - $N_0 = 3 \times 10^{18}$ cm^{-3}, 4 - $N_0 = 10^{19}$ cm^{-3}, 5 - $N_0 = 10^{20}$ cm^{-3}, solid lines - n = 2, dashed - n = 3.

It was shown in [2, 3] that inverted population can be realized in a decaying helium plasma for several transitions between the helium-ion levels. However, the amplification coefficients calculated in [3] were obtained under the hard-to-realize assumption that the plasma is optically transparent (Fig. 1, curves 1). Reabsorption of the radiation alters significantly the picture of the level population. The solution of the system of equations for the level-population kinetics [3], solved with allowance for reabsorption [4] for a homogeneous plasma in a cylinder of 1 cm diameter, has shown that when the helium ions in the ground state have a concentration $\sim 10^{15}$ cm^{-3} and higher, there is no inverted population for the n = 3 → n = 2 transition (Fig. 1, curves 2).

There exists an effect that eliminates, as it were, the influence of the reabsorption and restores the inverted population in an optically dense plasma. When an excited helium ion (excitation potential ≥ 40.8 eV) collides with a helium atom in the ground state (ionization potential = 24.6 eV) the atom can become directly ionized, and the ion can go over into the ground state. We can write for the cross section of such a process, in accord with [5]

$$\sigma = 2{,}3\,\pi a_0^2 \left[\frac{\sigma_{ph}(\omega)}{\pi a_0^2} \left(\frac{Ry}{\hbar\omega} \right)^2 f \frac{c}{v} \right]^{2/5}$$

where $\hbar\omega$ is the excitation potential of the ion level under consideration, f is the oscillator strength for the transition between this level and the ground state of the ion, $\sigma_{ph}(\omega)$ is the cross section for the photoionization of the atom, v is the

[1)]The possibility of obtaining generation of the helium-ion n = 3 → n = 2 transition in the regime of growing ionization is discussed in [1].

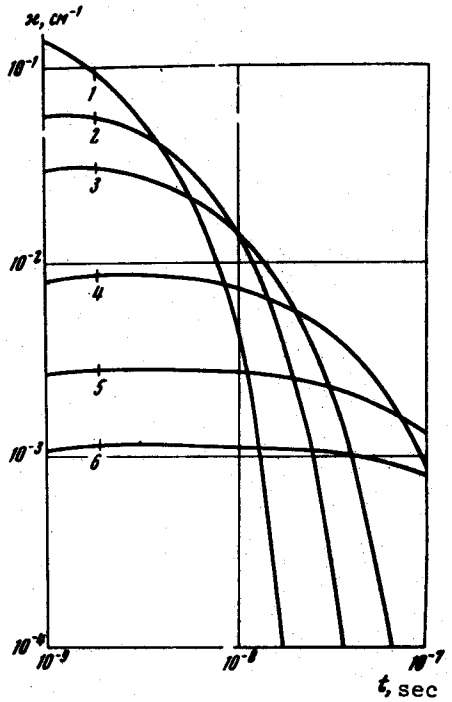

Fig. 2. Amplification coefficient for the 1641 Å line at $N_e = 10^{16}$ cm^{-3} and $N_0 = 10^{19}$ cm^{-3}; 1 - T_e = 0.2 eV, 2 - 0.3 eV, 3 - 0.4 eV, 4 - 0.6 eV, 5 - 0.8 eV, 6 - 1 eV.

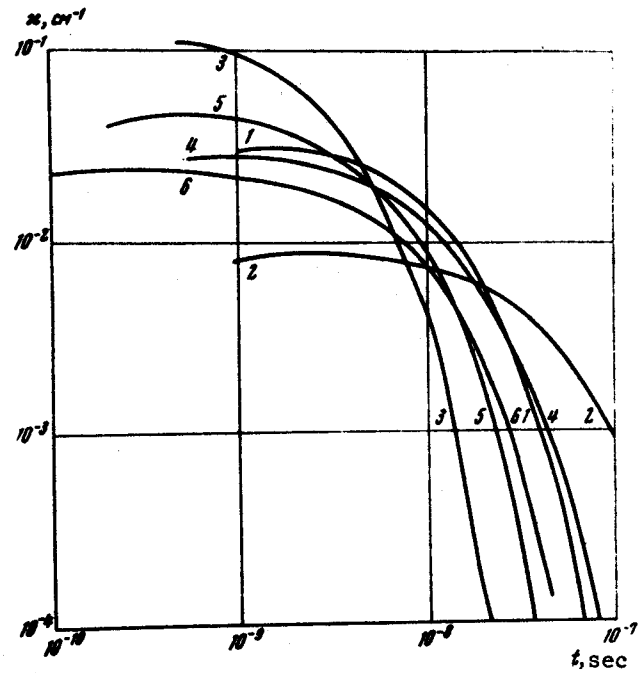

Fig. 3. Amplification coefficients for the 1641 Å line at different plasma parameters:

N_e, cm^{-3}	T_e, eV	N_0, cm^{-3}
1 – 10^{16}	1 – 0.4	1 – 10^{19}
2 – 10^{16}	2 – 0.6	2 – 10^{19}
3 – $2\cdot10^{16}$	3 – 0.4	3 – 10^{19}
4 – $2\cdot10^{16}$	4 – 0.6	4 – 10^{19}
5 – $5\cdot10^{16}$	5 – 0.8	5 – 10^{19}
6 – 10^{17}	6 – 1.2	6 – $4\cdot10^{19}$

relative velocity of the colliding particles, $Ry = me^4/2\hbar^2$, a_0 is the Bohr radius, and c is the speed of light. Substituting into this formula the values of f [6] and of $\sigma_{ph}(\omega)$ [7] corresponding to the collision of an ion in the state n = 2 with an unexcited atom, we obtain $\sigma = 1.3 \times 10^{-15}$ cm^2. At a temperature on the order of 0.5 eV we have $\langle\sigma v\rangle \sim 10^{-9}$ cm^3/sec. Thus, if the concentration of the helium atoms in the ground state is $N_0 \gtrsim 10^{19}$ cm^{-3}, the rate of depletion of the ion level n = 2 as a result of such a process exceeds the rate of radiative decay ($A = 8 \times 10^9$ sec^{-1}).

With increasing principal quantum number n, the cross section of this process decreases as a result of the decrease of both the oscillator strength f and the photoionization cross section $\sigma_{ph}(\omega)$. We can thus expect the ionization of helium atoms by collision with excited helium ions to lead to a predominant depletion of the lowest excited states and to creation of an inverted population.

Taking into account the process discussed here, we solved the system of equations of [3] with an electronic computer for the following plasma parameters: electron density $N_e = 10^{15} - 10^{17}$ cm^{-3}, density of the atoms in the ground state $N_0 = 3 \times 10^{18} - 10^{20}$ cm^{-3}, and electron temperature T_e = 0.2 - 1.4 eV. When choosing the initial conditions it was assumed that the concentration of the doubly-charged ions in $N^{++} = 0.01N^+$ [8, 9] and that the excited levels are not populated.

Figure 1 shows the time variation of the level population of an He^+ ion with principal quantum numbers n = 2 and n = 3 at $N_e = 10^{16}$ cm^{-3} and $T_e = 0.3$ eV for different values of N_0. Population inversion is realized for these levels at an atom density $N_0 > 3 \times 10^{18}$ cm^{-3} (this density depends on N_e and T_e). Figures 2 and 3 show the time dependence of the amplification coefficient κ for the $n = 3 \rightarrow n = 2$ transition ($\lambda = 1641$ Å) at different values of the plasma parameters. At densities $N_e \sim 10^{16} - 10^{17}$ cm^{-3} and $N_0 \sim 10^{19} - 4 \times 10^{19}$ cm^{-3} and at temperatures $T_e \sim 0.4 - 1.2$ eV, κ remains for the indicated line at the practically reasonable level $\kappa > 10^{-2}$ cm^{-1} up to the instant of time $t \sim 10^{-8}$ sec. The value of κ is determined by the ratio of the rate of level population during the recombination process (main dependence on N_e and T_e) to the rate of their depletion by ionization in collisions with the atoms (main dependence on N_0).

The time of cooling of the electrons [10] after a short ionization pulse turns out to be smaller than the time of existence of the inversion (in this case $T_i \simeq T_0$ [11]). On the other hand, the heating of the electrons during the recombination process is inessential, since only a small fraction of the electrons ($\sim N^{++}/N^+$) recombines during the time interval of interest to us.

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