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Simulation of processes in the solarphotosphere

Yu. A. Piotrovsky^a; Yu. A. Tolmachev^a

^a Institute of Physics, St. Petersburg State University, St. Petersburg, Russia

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SIMULATION OF PROCESSES IN THE SOLAR PHOTOSPHERE

Yu. A. PIOTROVSKY and Yu. A. TOLMACHEV

*Institute of Physics, St. Petersburg State University, Peterhof, St. Petersburg,
198904, Russia*

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Low-temperature plasma formed by an electron beam in helium is considered as a laboratory model of the solar atmosphere. Detailed analysis of the level excitation and destruction processes is performed. Good agreement between experimental data and the results of calculations is shown.

KEY WORDS Low-temperature plasma, atom-electron collisions

1 INTRODUCTION

For several years, a small group of researchers and students of the laboratory of Nonlinear Optics & Plasma Spectroscopy studies processes of the electron-atom collisions in low temperature helium plasma. To our surprise, we have observed that a pretty-small gas-filled electron gun can be considered as a laboratory model of the solar photosphere. The set of parameters of the plasma electron component falls within the range typical for the M – model, as it will be shown later.

Two general reasons are responsible for this coincidence. The first one is in that the ground-state atom concentration in our experiments was just the same as at the height of 100 km above the solar “surface”. The second reason is in general similarity of primary excitation-ionization mechanisms. In solar atmosphere as well as in our electron gun, excited atoms and ions are formed in the collisions of fast charged particles with ground-state atoms, and the state of plasma as a whole is to be treated as ionization-nonequilibrium.

2 EXPERIMENT

In our experiments, the electron gun of a specific construction was used (Figure 1). Four long plane thermocathodes with their active surfaces turned to the axis of the system formed the primary electron flow. To accelerate it, a parallelepiped made of

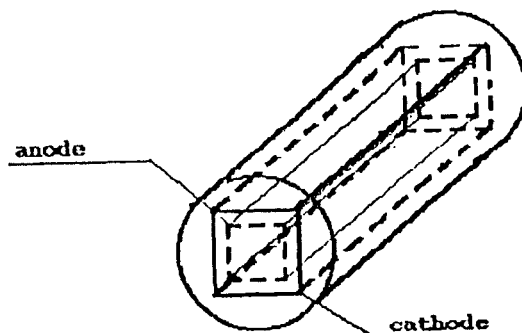


Figure 1 The electron gun.

tungsten wire grid was placed co-axially inside the cathodes. This grid was the anode of the diode system, and it bounded the region of equipotential space inside the electron gun that was studied in experiments. The resulting energy of electrons accelerated in the anode/cathode gap and penetrating inside the anode corresponded to the voltage applied to electrodes and, changing the cathode potential relative to the anode, one could form groups of monokinetic electrons of different energies. This enables, for example, to study stepwise ionization, recombination etc. In the experiments described here, four cathodes were connected one to another. Correspondingly, plasma inside the anode was formed by four reciprocally opposite beams of electrons with identical energies. The plasma luminescence was registered in the axial direction.

For the investigation of the kinetics of the processes of population and destruction of the levels, excitation of the gas was carried out by rectangular pulses with duration varying within the range from 5 to 50 μs ; the duration of the pulse front and cease at the 0.1 level was $< 0.25 \mu\text{s}$. This value is much lower than the characteristic time of plasma parameters, and we were able to neglect it in our analysis of the kinetics of the processes.

The dependence of the brightness of the HeI 501.5 nm line ($3^1P_1 - 2^1S_0$ transition) on time is shown in Figure 2. In this experiment, the energy of fast electrons was 100 eV, and it is well known that the direct excitation cross-section for n^1P_1 states is at least by two orders of magnitude greater than for any other nL state at such an energy. So the upper atomic level was excited directly from the ground state in our conditions, and all the secondary excitation/quenching processes play a small role for this state, as the estimates show. It is evident from Figure 2 that one can describe the observed dependence of brightness on time by a step function, with an adequate degree of accuracy. This means that the time dependence of the rate of excitation and ionization of particles by fast electrons in plasma can be considered as switched on and off.

For the analysis of the processes of excitation and destruction of excited states, we need information on the electron distribution function in plasma. For this pur-

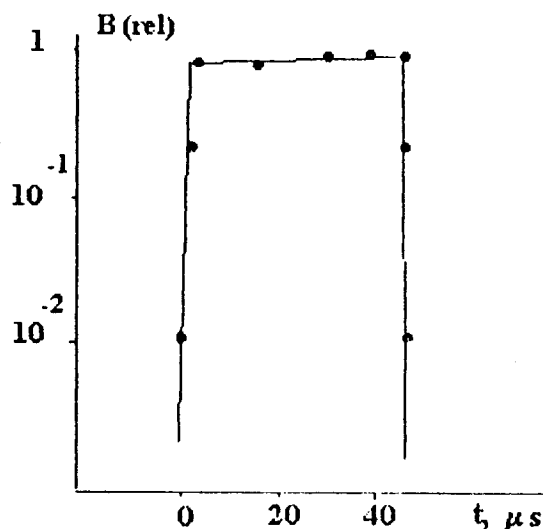


Figure 2 The luminiscence of HeI (501.6 nm).

pose, theoretical and experimental study of the electron parameters of plasma was carried out. The theory included solutions of kinetic equations for charged particles assuming rectilinear trajectories for fast electrons. For slow electrons, the diffusion equation was solved.

The experimental study of electron parameters was carried out by the probe method. Simultaneously, a special optical method was developed for helium plasma that permitted us to measure the electron density and the mean electron energy at the end of a current pulse.

The theoretical and the experimental results were in good agreement. The typical data for helium pressure 80 Pa and 100 V accelerating voltage are shown in Figure 3. The measurements have shown that, for a fixed pulse duration, the slow-electron concentration rises almost linearly with current. It was shown also that the distribution function of slow electrons can be described by the Maxwellian one, with the electron temperature 0.55 ± 05 eV. Note that this value fits quite well the solar photosphere conditions.

3 RESULTS OF EXPERIMENTS AND THEIR QUALITATIVE ANALYSIS

In the first experiments, we established a strong qualitative difference of the population dependence on time for the states with different principal quantum numbers. If, for the levels $n = 3, 4$, the brightness of the corresponding lines was practically constant during the excitation pulse, for higher states a maximum was observed at $t_{\max} = 2-5 \mu s$. The rate of the decay of the line brightness in the pulse after

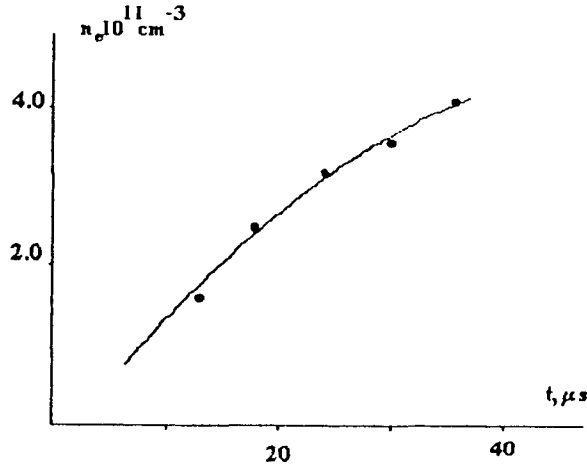


Figure 3 Electron concentration vs time, $J = 120 \text{ mA}$, $P_{\text{He}} = 0.8 \text{ Torr}$.

the maximum depended on n strongly, and it reached an order of magnitude for $n = 8 \dots 12$. It also grew with the increase of the l -number.

Considering the fact that the characteristic radiative lifetimes of the states studied are 10^{-7} – 10^{-6} s and the rate of excitation during a pulse is constant, one can describe qualitatively the observed time dependence of the line brightness in the following way. Population of a level is the result of direct excitation by fast electrons, and its rate does not change during the pulse. Formation of long-living particles takes place during the pulse, and inelastic collisions of excited atoms with these particles quench excitation. As a result, the population of the level decreases. Estimates reveal that only slow electrons with $n_e \sim 10^{11} \text{ cm}^{-3}$ show the rate of quenching greater than the rate of radiative losses. One can connect the formation of the brightness maximum at the beginning of the pulse with the rise of the quenching probability due to the accumulation of plasma electrons.

Let us analyse, in some more detailed form, the kinetics of the formation of a level populations during the current pulse. We consider a separate group of states with the principal quantum number n and different l, s values. These states form a block because of atom-atom quasi-elastic collisions that is characterized by the following parameters:

- effective probability γ_n of depopulation because of spontaneous emission and inelastic atom-atom collisions;
- the rate constant, K_n^e , of quenching in the collisions with electrons;
- the rate of direct electron excitation $\Gamma_n = [\text{He}_0] \mathbf{n}_e \sigma_{0n} \mathbf{v}_e$ (here after, the bold face is used for parameters related to fast electrons).

Using the approximation that the concentration of slow electrons in the pulse increases linearly with time, $n_e = \alpha t$, the kinetic equation for the population of a

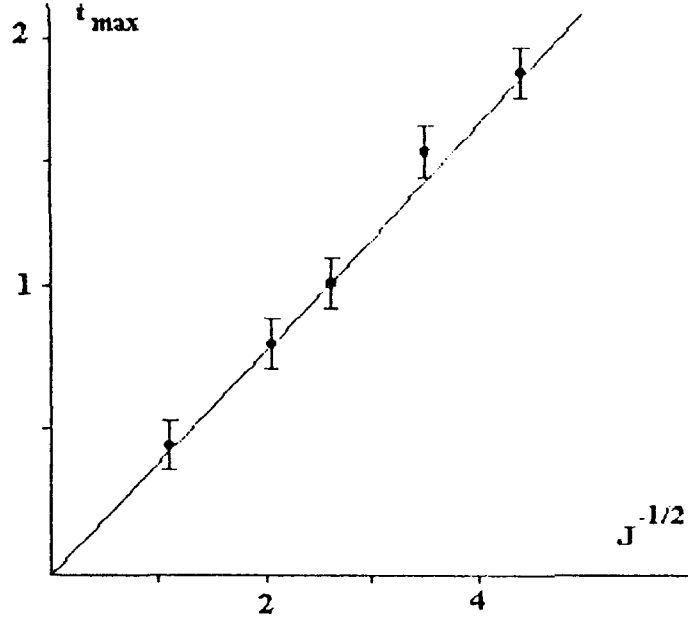


Figure 4 Position of the brightness maximum vs the pulse current.

level can be written in a form:

$$d[\text{He}_n]/dt = \Gamma_n - [\text{He}_n](\gamma_n + K_n^e \alpha t). \quad (1)$$

Its solution may be expressed with the Dawson integral, and for $[\text{He}_n] = 0$ at $t = 0$ and $\Gamma_n = \text{const}$ it has the form

$$[\text{He}_n] = \Gamma_n \exp \left[-(\gamma_n t + \frac{1}{2} K_n^e \alpha t^2) \int_0^t \exp(\gamma_n z + \frac{1}{2} K_n^e \alpha z^2) dz \right]. \quad (2)$$

This equation describes correctly the general character of the dependence of population on time and, in particular, the shape of the maximum and its position in time as a function of the beam current J . The calculated and measured dependence on current of the instant at which the maximum population is attained is shown in Figure 4. In the agreement with (2), the instant of the maximum (t_{max}) shifts toward the beginning of the pulse proportionally to $J^{-1/2}$, while the maximum brightness rises proportionally to $J^{1/2}$.

A quantitative investigation of the decay of line brightness after passing the maximum can be performed in a quasy-stationary approximation (the same result can be received by setting $t \rightarrow \infty$ in (2)):

$$[\text{He}_n] = \Gamma_n (\gamma_n + K_n^e \alpha t)^{-1}. \quad (3)$$

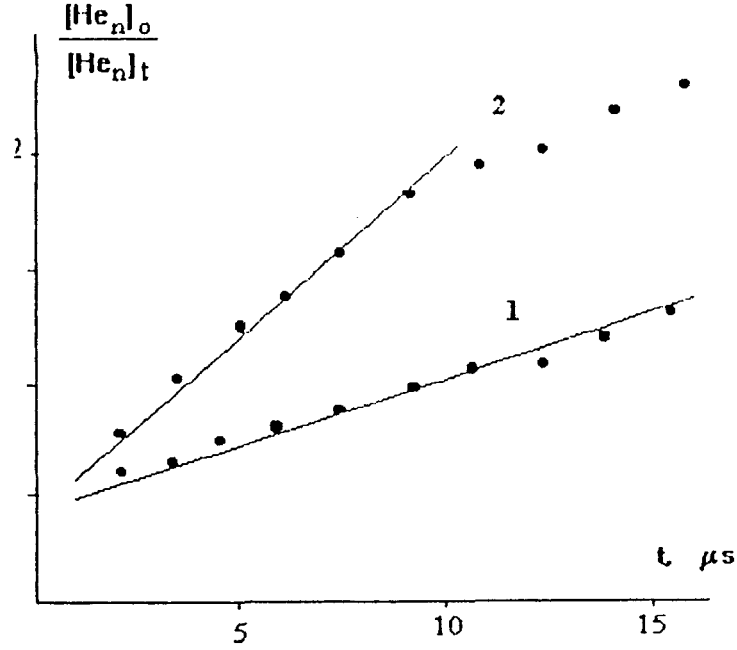


Figure 5 Inverse brightness of the HeI (355.4 nm) vs the pulse current, 1-20, 2-200 mA.

From (3), one obtains for the value of the inversed population of the level:

$$[\text{He}_n]^{-1} = (\gamma_n / \Gamma_n) + \alpha(K_n^e / \Gamma_n)t. \quad (4)$$

As shown in Figure 5, for $t > t_{\max}$ Equation (4) fits the experimental data satisfactorily.

In our paper (Piotrovsky *et al.*, 1992), the detailed concept of the block of states mixed by electron-atom and atom-atom collisions was developed. The most probable group of states that forms the n th block in helium consists of all levels with the same n and different l, s -values. If we assume that the transfer of excitation within this block takes place during a time interval essentially shorter than the lifetime of any state of the block, the statistical weight of this block is $g_n = \sum_{ls} g_{nls} = 4n^2$ while the effective probability of its quenching is

$$\gamma_n = \sum_{ls} \gamma_{nls} g_{nls} / \sum_{ls} g_{nls}, \quad (5)$$

where $\gamma_{nls} = A_{nls} + [\text{He}_0]K_{nls}^a$ (A_{nls} is the probability of radiative losses, and K_{nls}^a is the quenching rate constant for atom-atom collisions). Introducing

$$A_n = \sum_{ls} A_{nls} g_{nls} / \sum_{ls} g_{nls} \quad (6)$$

and the average quenching constant of the block

$$K_n^a = \sum_{ls} K_{nls}^a g_{nls} / \sum_{ls} g_{nls}, \quad (7)$$

one obtains the modification of (5):

$$\gamma_n = A_n + [\text{He}_0] K_n^a \quad (8)$$

which demonstrates that a block of states mixed with respect to population shows itself in the experiment as a single level with radiative lifetime and quenching rate constant described by (6) and (7).

Measurements of the effective decay probabilities of level population under our experimental conditions were the following step of the study. The decay of brightness of the spectral lines after the end of excitation pulse was measured. Varying the pulse duration, it was possible to trace the dependence of γ on electron concentration and to extrapolate it to $n_e = 0$. The effective decay probabilities obtained in such a way differed significantly from the calculated ones. Some independent experiments were performed to verify the obtained data on the effective lifetimes. They showed that the resulting error of our measurements did not exceed 20–25%, while the calculated and measured data differed by several times.

As a possible reason of this discrepancy, one can assume the electron-excitation collisions leading to stepwise ionization from the state under consideration. The semiempirical approximation for the rate constant of this process proposed by Biberman *et al.* (1989) was used for calculations. Under the conditions of our experiment, for Rydberg states with $n > 4$, it can be written in the form:

$$K_{ni}^e = 2.6 \times 10^{-7} n^2 T_e^{-1/2} \exp(-23/n^2 T_e) \approx 2.6 \times 10^{-7} n^2 T_e^{-1/2} (1 - 23/n^2 T_e). \quad (9)$$

4 THE FIRST ORDER THEORY. A STATIONARY SYSTEM

Calculations using (9) showed that stepwise ionization by slow electrons provided only 10% of the obtained quenching-rate constants.

For the further development of the experimental data interpretation, the multi-step processes of excitation transfer between close-lying levels were taken into account. The results of the modified diffusion-approximation (MDA) theory (Biberman *et al.*, 1989) were used. We considered the highly-excited helium levels as hydrogenlike and the population of states with the same n as mixed with respect to l and s . The problem was simplified by using the assumption that the excitation transfer took place only between levels n and $n \pm 1$; the rate constants $K_{n,n+1}^e$ and $K_{n,n-1}^e$ were taken from Biberman *et al.* (1989).

The estimates have shown that the rates of energy transfer to any n -state from the states $n + 1$ and $n - 1$ are of the same order of magnitude or even exceed the ionization rate.

The infinite system of equations for the quasi-stationary approximation has the following form:

$$[\text{He}_{n-1}]n_e K_{n-1,n}^e - [\text{He}_n](\gamma_n + n_e K_{ni}^e + n_e K_{n,n+1}^e + n_e K_{n,n-1}^e) + [\text{He}_{n+1}]n_e K_{n+1,n}^e = \Gamma_{0n}. \quad (10)$$

At the assumption that the rate of slow electron - excited atom collisions is small with respect to radiative losses (i.e. for $n_e \rightarrow 0$), one has the trivial result:

$$[\text{He}_n]^0 = \Gamma_{0n}/\gamma_n. \quad (11)$$

The population of all the hydrogenlike states is independent on n . This is because the total excitation cross-section from the ground state decreases as n^{-3} , while lifetime increases as n^3 . (By the way, we observed such a distribution at low current densities for n^3D states).

One can obtain a similar result using (10) for the block of levels with the same n . In fact, the block population is determined by the excitation of n^1P_1 levels, the rate of which decreases with n as n^{-3} , while the effective lifetime of the block increases as $n^5/\ln n$, according to Theodosiou (1984). Neglecting the logarithmic correction, one has for the total population of the block $N \sim n^{-3}n^5 = n^2$. Taking into account the increase of the statistical weight of the block as n^2 , one can see that, relative to the unit of statistical weight, the population must not depend on n .

It is also not difficult to consider a somewhat more complicated situation when the population of levels decays with n according to a power law (Tolmachev, 1968):

$$[\text{He}_n] = An^{-p}. \quad (12)$$

The value of p here is 5-6 (Tolmachev, 1968; Hirabayasi, 1988). So one obtains approximately:

$$[\text{He}_{n+1}] = [\text{He}_n](1 - p/n). \quad (13)$$

Then

$$[\text{He}_n] = \Gamma_{0n} \{ \gamma_n + n_e [(K_{n,n-1}^e - K_{n-1,n}^e + (K_{n,n+1}^e - K_{n+1,n}^e) - (p/n)(K_{n-1,n}^e - K_{n+1,n}^e) + K_{ni}^e)] \}^{-1}. \quad (14)$$

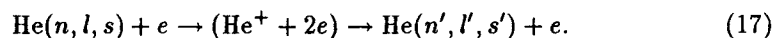
Using, for the $n \rightarrow n+1$ excitation transfer rate constant $K_{n,n+1}^e$, the relationship given in Biberman *et al.* (1989), applying the detailed balance principle to determine the rate of the inverse process, and taking into account the fact that the distance between high-excited levels is $\Delta E_{n,n+1} \ll kT_e$, one obtains to the second order of accuracy:

$$[\text{He}] = \Gamma_{0n}/[\gamma_n + n_e K_{ni}^e + n_e K_n^e], \quad (15)$$

where

$$K_n^e = K_n^e(p) = 1.6 \times 10^{-7} n^2 T_e^{-1/2} [(p+3) + (p-1)(13.6/n^2 T_e)]. \quad (16)$$

It can be noticed that not only K_n^e and K_{ni}^e are of the same order of magnitude for large n values, but also that they have the same dependence on the principal quantum number and T_e . We suppose that this fact reflects the role of the probable channel of electron-atom interaction in the collision through virtual transition via continuum:



As far as we know, this channel has not been strictly taken into consideration by the theory.

In the equations (14, 16), the value of the parameter p remained unknown. We performed the calculations using $p = 0$ (uniform distribution) and 5 according to (16). Comparisons with the experiment show that, for the majority of cases, the obtained $K_n^{\text{exp}}(p)$ values lie in the interval between $K_n^e(0)$ and $K_n^e(5)$.

The experimental data and the results of calculations described, have obviously shown that neither the stationary distribution of level population nor its dynamics can be correctly described without taking into account inelastic collisions between the high-excited atom and electrons that lead to ionization and to excitation transfer onto the nearby levels. Nevertheless, the systematic divergence between the calculated and measured effective lifetimes of different levels was observed that made us analyse a much more complicated scheme of the processes.

5 THE SECOND ORDER THEORY. A STATIONARY SYSTEM

For the next step of our analysis, a new numerical model was formulated. It consisted of the following combination of excitation and quenching processes:

- direct excitation by the beam of primary electrons emitted from the cathode;
- spontaneous photon emission;
- excitation transfer between Rydberg states and ionization caused by collisions of high-excited atoms with thermal electrons as well as collisional recombination.

Different l -states were supposed to be degenerated in energy, but no primary population l -mixing was assumed.

The electron spin was neglected and the hydrogen approximation for Rydberg states of binding energy for the helium atom was adopted. The specifics of helium was taken into account only in terms of the direct excitation and ionization cross section relation for different levels and the corrections to resonance radiation trapping.

The existing ratio of the direct excitation cross sections in helium allows us to adopt in the first approximation that only nP -levels are populated from the ground state by fast electrons. This means that our calculations supposed the existence of strong selectivity in the distribution of the excitation flux between different series of levels.

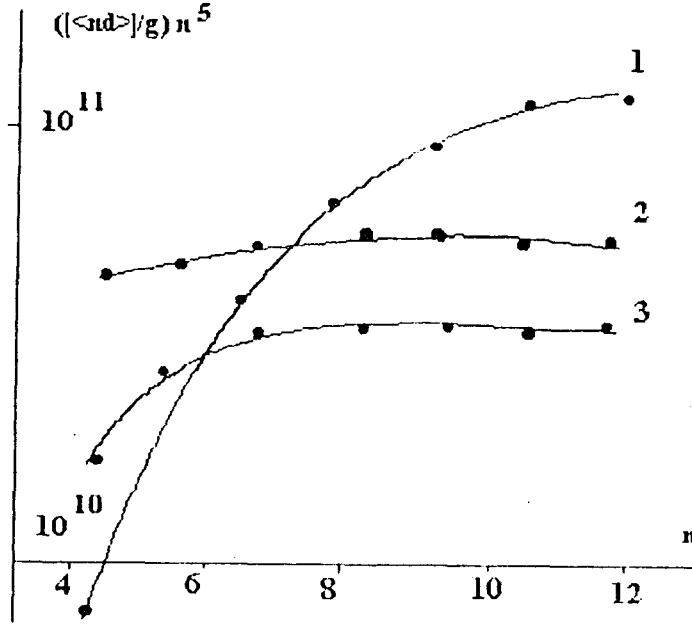


Figure 6 Establishing the dependence $Nn^5 = \text{const}$; 1, $n_e = 10^{10} \text{ cm}^{-3}$; 2, $n_e = 10^{11} \text{ cm}^{-3}$; 3, $n_e = 10^{12} \text{ cm}^{-3}$.

The set of levels with $n = 2 \dots 15$ and $l = 0 \dots n - 1$ was taken. Spontaneous radiative processes between excited states, according to our estimations, have only a small effect on the Rydberg-state populations and we neglected them, but we included the total radiative losses whose probability was calculated according to Besuglov (1983):

$$A = \frac{0.107 \times 10^{11}}{n^3(l - 1/2)^2}. \quad (18)$$

This relationship is not correct for s -states, in this case we considered the values obtained as an estimate only.

Following Tolmachev (1968), we assumed that slow electrons caused the transitions between the states $\langle n, 1 \rangle \leftrightarrow \langle n \pm 1, 1 \pm 1 \rangle$ only:

$$K = 1.6 \times 10^{-7} \frac{n^2(n-1)^3}{(2n-1)^3 T^{-1/2}}. \quad (19)$$

The rates of the inverse processes were calculated using the detailed balance principle. For the stepwise ionisation we use:

$$K_i(n) = 4.3 \times 10^{-8} \frac{n^3}{(E_n/T_e)^{1/2} \exp(E_n/T_e)}. \quad (20)$$

Concerning the transitions with $\Delta l = 1$, $\Delta n = 0$, we have no information on their cross-sections. Several calculations were fulfilled in which the rate constant of

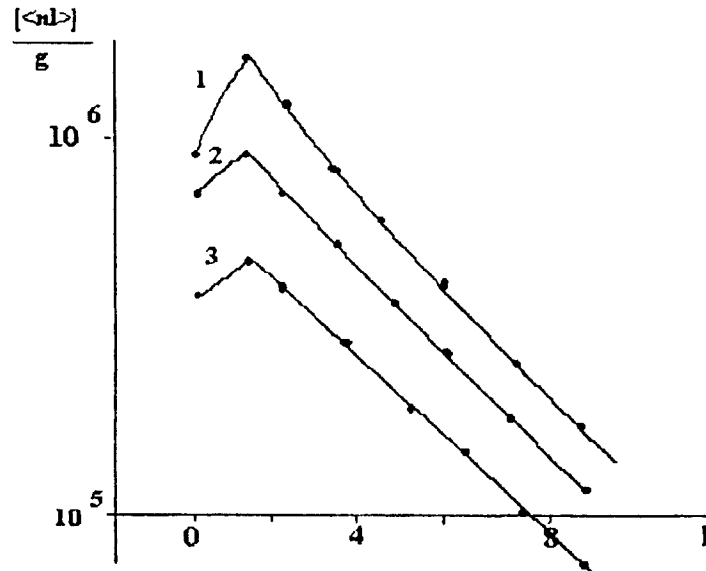


Figure 7 Population distribution over l (for the states with $n = 10$).

such a transition was taken to be $r = 0; 0.1; 1.0; 10$ times the rate constant of the processes with $\Delta l, \Delta n = 1$.

As a result, the total system of the processes included direct excitation of nP -levels and collisional-radiative recombination for the only excitation sources, and emission of radiation and stepwise ionization for quenching. In these terms, all other inelastic collisions are to be classified as excitation transfer processes between different (n, l) states, i.e. as mixing processes.

Calculations were fulfilled for $T_e = 0.55$ eV and $n_e = 10^{10} \dots 10^{13}$ cm $^{-3}$.

To test the reliability of the described model, the calculations of the population distribution over n and l were performed for the conditions close to ours but with $T_e = 5$ eV (Tolmachev, 1968). We obtained satisfactory agreement between the calculated data and measured dependences under the r -value 0.1. Thus the transitions between the levels with the same n are less probable by an order of magnitude than with $n = \pm 1$. For $T_e = 0.55$ eV, a similar comparison has given $r = 0.1 \dots 1$.

The most meaningful data, in our opinion, are shown in Figures 6–8. The concentration of excited atoms in states belonging to same series, under conditions for which the recombination populations can be neglected, obeys the law $Nn^5 = \text{const}$ with the accuracy of 20–30%. Levels with large l are much worse populated at a unit of statistical weight than those with small l , and the decrease of their population over l has an approximately exponential character. Finally, the increase of the electron concentration from 10^{10} to 10^{12} cm $^{-3}$ causes a fall of the concentration of excited atoms (i.e. quenching). It can be noticed that the deviation from the simple dependence $N(n_e) \sim (A + kn_e)^{-1}$ pointed out above agrees completely with

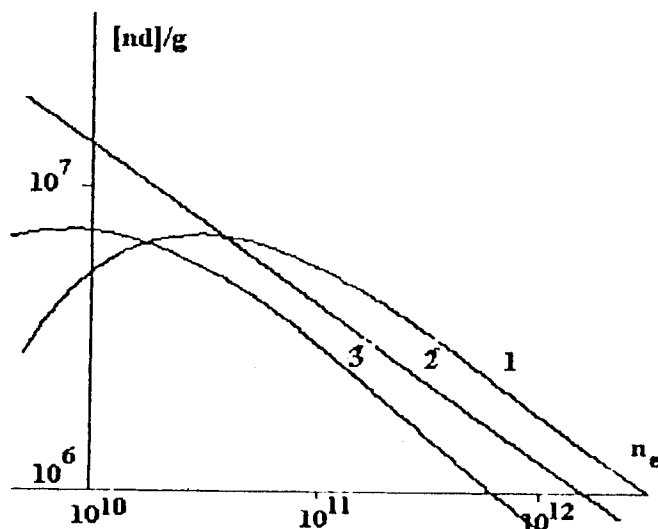


Figure 8 Population vs concentration for a fixed excitation rate $n = 1-5, 2-7, 3-10$ (population multiplied by 10 for 3).

the results of calculations. Calculations of the population and deexcitation flows for any level show that they compensate each other to the first approximation. So the general conclusion for the concentration of excited atoms given by (15) is valid not only for the population-mixed states but for the case when the term structure is taken into account in detail.

6 THE SECOND ORDER THEORY. A NON-STATIONARY SYSTEM

After the solution of the stationary problem, the dynamics of population variation in time was studied. A system of 120 linear differential equations was solved. All the processes enumerated above were taken into account. The direct excitation flow for n^1P_1 -states was fixed during the pulse, zero initial population of all levels was assumed. Figure 9 shows the results of calculations for different l -sublevels of the $n = 10$ state. In full accordance with the experimental data, the later is the position of the population maximum formed, the larger is the effective lifetime of the state. Figure 9 shows also that the populations of all the sublevels at a given n change similarly one to another. Such a unification is observed beginning from $n_e = 2 \times 10^{10} \text{ cm}^{-3}$, this value is achieved in the experiment, for the given example, at $t = 2\mu\text{s}$. A similar dependence is observed for different n -levels, i.e., beginning from this instant, it is possible to suppose the formation of a quasistationary state population distribution.

Following Eq. (2), we can examine the dependence of the position of the population maximum in the time scale on the direct excitation rate (it corresponds to

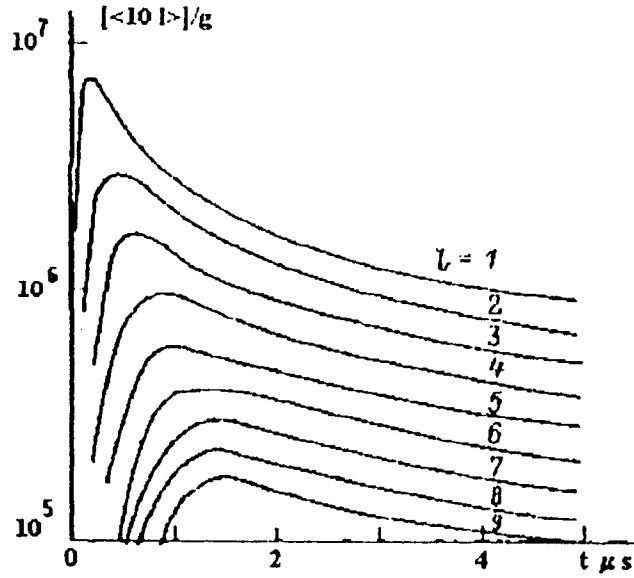


Figure 9 Population vs time after beginning of excitation for the (10l) states.

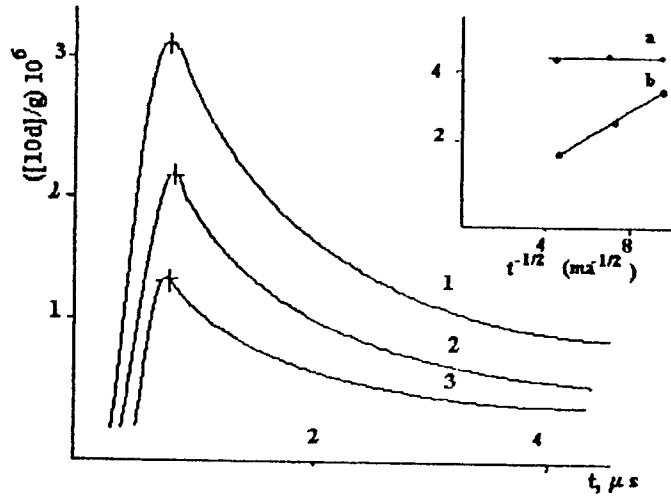


Figure 10 Population of (10d) states for different currents; 1-100, 2-50, 3-25 mA. Inserted: the dependence of $t_m \sqrt{J}$ (a) and $g_{(10d)}$ (b) vs $J^{-1/2}$.

the current increase in the experiment). As it follows from (2), the instant of maximum population is $t_m \sim J^{-1/2}$, and the brightness in the maximum is $I \sim J^{1/2}$. Figure 10 shows that these dependences are well-obeyed (the 10d state is

shown for an example). (In this analysis we found that, increasing n from 7 to 12, the corresponding change of t is only by a factor of 1.5–2). The maximum of the population is formed at the moment when the quenching collisions probability reaches the magnitude which is equal to the probability of radiative losses. Thus we can conclude that the developed numerical model gives a good description of the experimental data for the population distribution of Rydberg states and their dependence on the excitation conditions.

As one can see, a group of experiments described permits us to claim that a rather simple gasdischarge cell offers a good model for the photosphere of sun-like stars. Moreover, it can demonstrate in detail the properties not only of a steady-state atmosphere but also of processes in flashes and spikes. Using high-current-density discharges in gas mixtures, it seems possible also to perform an experimental study of the processes at high magnetic fields to simulate also non-stationary processes in solar plasma.

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