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05

Atomic kinetics in plasma under the action of laser pulses

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The problem of correctly constructing atomic kinetics in plasma under the action of laser pulses of various durations is considered. Based on the use of the generalized probability of temporal evolution of the photoprocess, calculations of laser fluorescence signals on helium lines in plasma with temperature $\approx 10\,\mathrm{eV}$ and density $\approx 10^{12}\,\mathrm{cm}^{-3}$ were performed. The laser pumping and fluorescence scheme was modeled for the E-1 setup plasma (prototype of an electrode-less plasma rocket engine) for different numbers of modes in the pulse. Data on the temporal evolution of the populations of levels responsible for the fluorescence signal under the action of laser pulses are presented.

Keywords: laser pulse, plasma, atomic kinetics, perturbation theory.

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Introduction

The problem of constructing a generalized radiation-collisional model for the population of atomic states in plasma under the action of collisions with charged particles and laser radiation pulses of various durations is considered. The problem is relevant for the correct interpretation of laser fluorescence experiments in plasma. Unlike standard atomic kinetics, which is based on the concept of stationary transition rates per unit time between atomic levels, the generalized complete probability of temporal evolution of the photoprocess is used [1–3]. Calculations of the populations of atomic levels determining the fluorescence signal under the action of laser radiation on singlet transitions $3^1S{-}2^1P$ with pumping on the transition $2^1S{-}3^1P$ in helium plasma were performed. Analytical expressions describing changes in the populations of excited levels participating in the singlet laser pumping scheme of the helium atom were obtained.

The basis of the laser diagnostics system is a dye laser, pumped by the second/third harmonic of a solid-state Nd:YAG laser with a frequency of 20 Hz. Laser diagnostics is used to determine the axial velocity and temperature of helium atoms for the E-1 setup plasma. The characteristic pulse duration was 5 ns [4]. The main plasma parameters were taken to be characteristic of the E-1 setup plasma ($T_e = 10\,\mathrm{eV}$, $N_e = 10^{12}\,\mathrm{cm}^{-3}$). The lifetimes of excited levels are inversely proportional to the radiative decay coefficients. For the considered system of singlet states of neutral helium, only the lifetime of the $2p$ level is comparable to the 5 ns laser pulse duration; for the other levels, the decay times exceed the pulse duration.

The laser resonator length is 30 cm, and the intermode spacing is 0.65 pm. At a generation line width of 4−6 pm there will be 6−10 longitudinal laser modes in the generation spectrum.

The spectral profile of the laser pulse is represented as an envelope of pulses at various carrier frequencies. The obtained analytical expression for the population of the upper excited level was used to describe the change in the fluorescence signal in the laser pulse field. A comparison of populations depending on the number of modes accounted for in the calculation to describe the laser pulse shape was performed:

1) short-duration pulse,

2) several modes with intermode spacing of 0.65 pm.

Determination of the population of the 3p level of neutral helium for various representations of the spectral power density of induced excitation

To account for the influence of laser excitation on the $2s-3p$ transition in the balance equations describing the dynamics of populations, terms describing non-stationary excitation by laser pulses are introduced (Fig. 1):

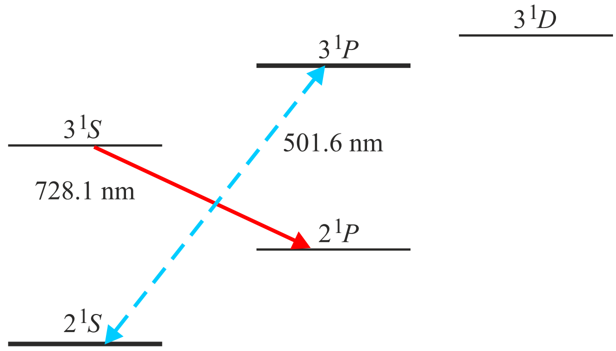

Figure 1. Scheme of the singlet levels of the helium atom accounted for in the radiation-collisional model.

$$\begin{cases} \dfrac{s_{2ns}}{dt} = -(C + w(t))n_{2s} + D_1 n_{2p} + E_1 n_{3s} + (A_1 \\ \qquad + w(w(t)))n_{3p} + F_1 n_{3d} \\ \dfrac{dn_{2p}}{dt} = C_2 n_{2s} - D_2 n_{2p} + E_2 n_{3s} + A_2 \mathbf{n}_{3p} + F_2 n_{3d} \\ \dfrac{dn_{3s}}{dt} = C_3 \mathbf{n}_{2s} + D_3 n_{2p} + A_3 n_{3s} + A_3 n_{3p} + F_3 n_{3d} \\ \dfrac{dn_{3p}}{dt} = (d_4 + w(\mathrm{t}))n_{2s} + D_4 \mathbf{n}_{2p} + E_4 n_{3s} \\ \qquad -(A_4 + w(\mathbf{t}))n_{3p} + F_4 n_{3d} \\ \dfrac{dn_{3d}}{dt} = c_5 n_{2s} + D_5 n_{2p} + E_5 n_{3s} + A_5 n_{3p} - F_5 n_{3d} \end{cases}, \quad (1)$$

where $w(t)$ is the transition rate per unit time under the action of pulses.

The coefficients $A_1{-}A_5$, $C_1{-}C_5$, $D_1{-}D_5$, $E_1{-}E_5$, $F_1{-}F_5$ are determined through the excitation and relaxation rates of transitions, Einstein coefficients for spontaneous emission, and ionization rates [5,6]. he considered system corresponds to a sufficiently low helium concentration (helium as an impurity in fusion systems and the main component in plasma flow — in both cases, its concentration in the ground state is on the order of $10^{12}\,\mathrm{cm}^{-3}$ and on the excited states responsible for fluorescence, it is 4 orders of magnitude lower). As a result, on distances of about 10 cm (size of the wall region of tokamaks (toroidal chamber with magnet coils) or engine chamber), the optical thickness $\sim 10^{-2}$.

The probability of the photoprocess under the action of pulses with duration τ per unit time in the framework of perturbation theory is

$$w(t) = \frac{d}{dt} W(t, \tau). \quad (2)$$

The photoexcitation probability at time t has the form [1–3]

$$W(t, \tau) = \omega_0 \Omega_0^2 \int_0^\infty G(\omega) \frac{\tilde{D}(t, \tau, \omega)}{\omega} d\omega, \quad (3)$$

$$\tilde{D}(t, \tau, \omega) = \left| \int\limits_{-\infty}^{t} \exp(i\omega t') \tilde{E}(t', \tau) dt' \right|^2 \quad (4)$$

— the square of the modulus of the incomplete Fourier transform of the dimensionless electric field strength in the laser pulse (or D-function),

$$w(t) = \omega_0 \Omega_0^2 \int\limits_0^\infty \frac{G(\omega)}{\omega} \frac{d}{dt} \tilde{D}(t, \tau, \omega) d\omega. \quad (5)$$

For an exponential pulse

$$E_{\mathrm{EP}}(t, \tau) = \theta(t) E_0 \exp(-t/\tau) \cos(\omega_c, t). \quad (6)$$

The exponential form of the laser pulse well describes the Q-switching mode (short-pulse generation mode) in which the dye laser operates (it has a sharp rise followed by a smooth decay). In the considered case, the choice of shape for the mathematical representation of the pulse is not so important; the main condition is a rapidly rising function at the initial moment of time.

The D-function in this case takes the form for the multicyclic case (when many oscillation periods fit within the pulse duration $\omega_c, \tau \gg 1$):

$$\tilde{D}_{\mathrm{EP}}(t, \tau, \omega) \simeq \frac{1}{4} \theta(t) \tau^2$$
$$\frac{1 + \exp(-2t/\tau) - 2\exp(-t/\tau)\cos[(\omega - \omega_c)t]}{1 + \tau^2(\omega - \omega_c)^2}, \quad (7)$$

where $G(\omega)$ is the Doppler absorption line profile. The thermal velocity significantly exceeds the macroscopic velocity for plasma engines, so the Doppler profile responsible for radiation absorption is dominant. Directed motion is insignificant for the direction of the laser beam across the directed velocity.

In the case of several longitudinal modes in the pulse with the same duration τ and different carrier frequencies, for the number of longitudinal modes $2N$ function (12) takes the form (for a Gaussian amplification profile in the laser and in the absence of correlation between modes)

$$D_N(t, \omega, \tau, \omega_c, \Delta, N)$$
$$= \sum_{j=-N}^{N} D(t, \omega\tau, \omega, \tau, \omega_c\Delta, j) \times \exp\left(-\left(\frac{j}{N}\right)^2\right). \quad (8)$$

The function D under the summation sign in formula (8) is given (for an exponential pulse) by formula (7), in which the carrier frequency of each longitudinal mode is replaced by the sum:

$$\omega_c \to \omega_c + j\Delta, \quad (9)$$

where Δ is the intermode frequency. Thus, the laser spectrum width is determined by the number of modes. From formula (5), two limiting cases of ultrashort and long pulses can be obtained.

1. Ultrashort pulse limit $\tau < T_2^*$ $w(t)$is independent of the Doppler profile of the transition line:

$$\omega(t) = \frac{1}{2} \pi \Omega_0^2 \frac{\tau}{\pi} \theta(\mathbf{t}) e^{-\frac{2t}{\tau}}, \quad (10)$$

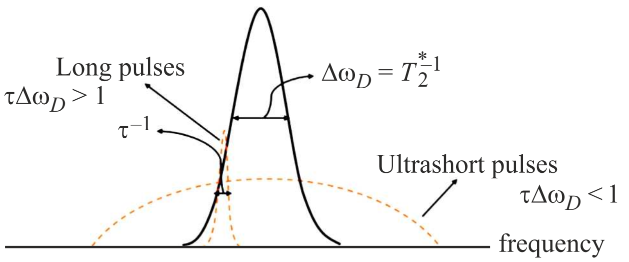

Figure 2. Spectral line profile in comparison with the laser pulse duration. T_2^* is the Doppler relaxation time, τ is the pulse duration.

where Ω_0 is the Rabi frequency,

$$\Omega_0 = \sqrt{\frac{3f_0 I/I_a}{2\omega_0/\omega a}}\omega_a, \tag{11}$$

f_0 is the oscillator strength of the transition, I is the maximum intensity of the laser pulse,

$$I_a = 3.52 \cdot 10^{16}\,\text{W/cm}^2, \quad \omega_a = 4 \cdot 10^{16}\,\text{c}^{-1}(27.2\,\text{eV}).$$

2. Long pulse limit $\tau > T_2^*$containing the Doppler profile:

$$\frac{1}{\pi}\frac{\tau^{-1}}{(\omega-\omega_c)^2+\tau^{-2}} \to \delta(\omega-\omega_c), \tag{12}$$

$$w(t) = \pi G(\omega_c)\Omega_0^2\theta(t)e^{-\frac{2\cdot t}{\tau}}, \tag{13}$$

A principal distinction is the difference between the laser pulse excitation rates (10) and (13) from the ratio of duration to the Doppler relaxation time $\Delta\omega_\text{D}\tau \left(\frac{T_2^*}{\tau}\right)$ (Fig. 2).

Results

1. Results of calculating the non-stationary population of the singlet $3p$ level of neutral helium under the action of a multimode laser pulse with intensity $I\,(\text{W/cm}^2)$, the probability of the photoprocess per unit time under the action of ultrashort pulses in the framework of perturbation theory, are presented.

The kinetics is expressed through the generalized transition probability per unit time $w(t)$obtained in the framework of perturbation theory. The dependence of the temporal evolution of populations on different pulse durations and numbers of modes was investigated. The calculation results are shown in Fig. 3, $a-c$ for the model two-level system 2^1S-3^1P. The initial population values before the laser pulse action for the above plasma parameters are $N_{3P}/N_{1S} = 1.1 \cdot 10^{-6}$, $N_{2S}/N_{1S} = 7.7 \cdot 10^{-5}$. It can be seen that with increasing laser pulse duration, the dependence on the number of modes decreases.

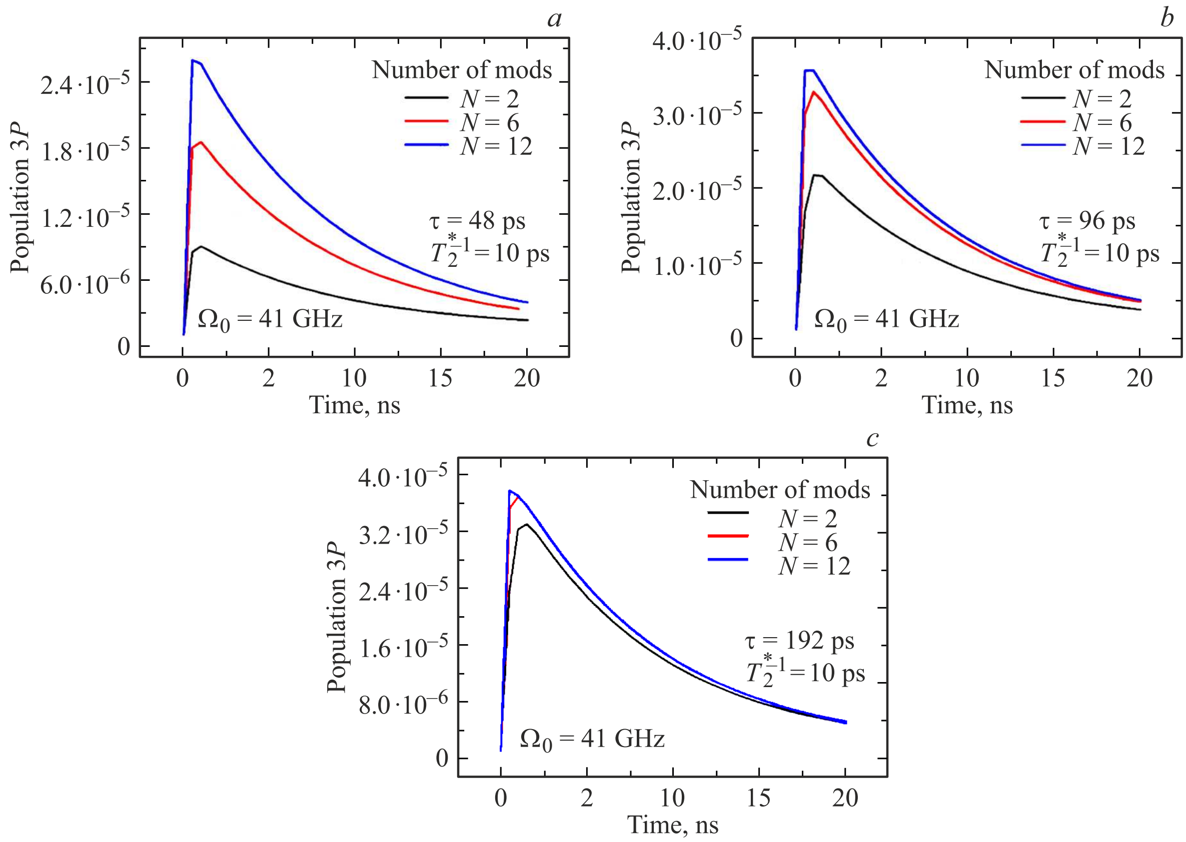

Figure 3. (a, b) Population of the $3p$-level of singlet helium during excitation by a multimode laser pulse on the $2s-3p$ transition with durations of 48 and 96 ps. (c) Population of the $3p$-level of singlet helium during excitation by a multimode laser pulse on the $2s-3p$ transition with duration of 192 ps.

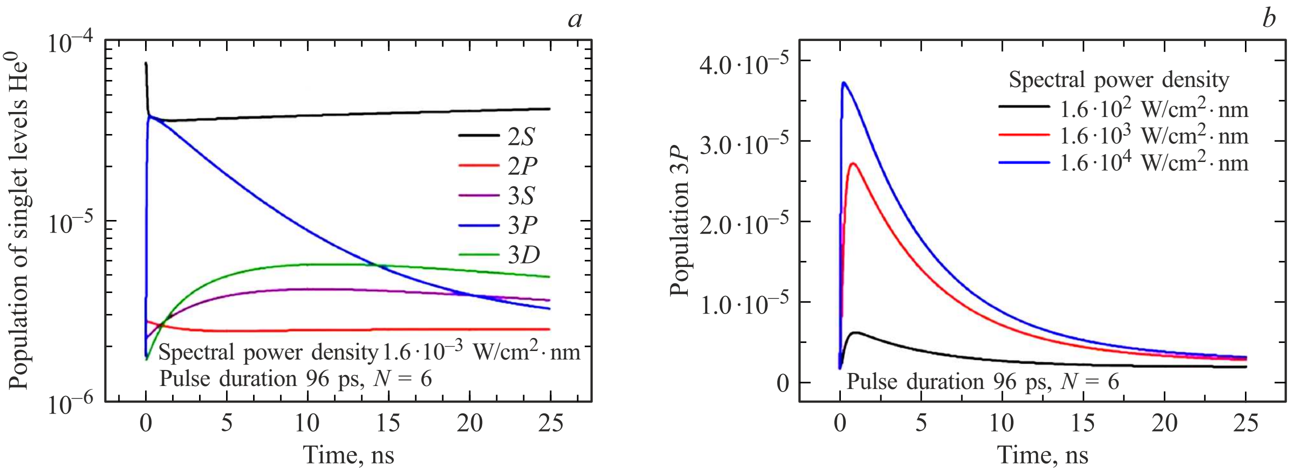

Figure 4. (a) Evolution of populations in a five-level system of various helium states under the action of a laser pulse on the $2S-3P$ transition (spectral power density 10^4 W/cm^2·nm, duration 192 ps), (*b*) dependence of the population of the $3P$ level of neutral helium on the laser pulse intensity.

2. Results of calculating changes in the population of singlet levels of neutral helium in a five-level system (Fig. 1) under the action of a laser pulse in the short-pulse approximation (10) are presented in Fig. 4, *a*. The dependence of the population of the $3P$ level of neutral helium on the laser pulse intensity is shown in Fig. 4, *b*.

Conclusion

Calculations of the evolution of atomic level populations determining the fluorescence signal under the action of laser radiation on singlet transitions in helium plasma were performed using the generalized photoprocess probability. The influence of multimodality becomes insignificant when the population approaches the saturation level.

The performed calculations allow accounting for the influence of laser fields with various spectral and temporal characteristics in the analysis of experimental results using LIF for plasma setups, in particular for the E-1 setup plasma.

Conflict of interest

The authors declare that they have no conflict of interest.

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