Features of x-ray spectra of a plasma produced by a subnanosecond laser pulse

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We investigate the x-ray spectra of multiply-charged ions produced when a plasma is heated by laser pulses of 250 psec duration and 5 J energy. Besides the lines formed by high-multiplicity ions, transition lines of ions of comparatively low multiplicity were recorded, although the plasma-electron temperature reached 1 keV and the electron density reached a value on the order of 10^{21} cm^{-3}. The presence of low-multiplicity ion lines can be attributed to the nonstationary character of the ionization process when the plasma is heated by a subnanosecond pulse since conditions are then produced in the plasma under which the pulse duration is sufficient for the electrons to heat up quickly but the ions cannot reach the ionization state corresponding to the given electron temperature. These conditions must be produced in the plasma to obtain population inversion in the far-vacuum ultraviolet and soft x-ray regions. The plasma-electron temperature and density were determined from the obtained spectra under the assumption that plasma heating was nonstationary.

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INTRODUCTION

For high-temperature laser-induced plasma heating, lasers with different pulse-duration (10^{-11}–10^{-7} sec) are employed. If the duration of the heating pulse is shorter than characteristic plasma times such as the expansion time, the recombination time, the electron-ion thermalization time, etc., the heating process is nonstationary. This nonstationary character must show up in the spectra of multiply-ionized atoms, since the ionization and level-population processes require certain lengths of time. The nonstationary mode of plasma heating is of special interest for population inversion in the far vacuum ultraviolet and shoft x-ray regions. [1] Thus, to obtain population inversion in the manner proposed by A. N. Zherikhin *et al.*, [2] it is necessary to excite high-lying levels of ions having a fairly low multiplicity of ionization. This in turn requires that the plasma contain sufficiently fast electrons, i.e., a high electron-temperature T_e and, concurrently, ions with a low multiplicity of ionization, i.e. a sufficiently low ionization temperature T_z. Furthermore, to lessen the Doppler broadening, it is desirable to have a plasma with the lowest possible ion temperature T_i. These conditions are expected to be obtainable by nonstationary heating of the plasma by ultrashort laser pulses (USP).

The most serious shortcoming of the use of USP for plasma heating is the comparatively low energies of the laser ray and of the plasma radiation, which may make it difficult to record the x-ray spectrum. The limit on the USP energy is imposed by the high power of the pulses. At fixed laser-amplifier parameters, the only way to increase the USP energy is to increase the pulse duration. In our experiments, we used USP of 250 psec duration as a compromise. The energy of the laser ray was then sufficiently high to ensure reliable registration of the spectra, and the pulse duration remained shorter than the characteristic times of the plasma.

THE EXPERIMENTAL INSTALLATION

The installation we set up for the procurement of plasma x-ray spectra consisted of a multistage USP YAG and neodymium glass laser, a target chamber, and a spectrograph. A detailed description of the functioning of the laser is given by A. N. Zherikhin *et al.* [3] In the amplification of USP, the principal effect that limits the growth of the brightness is the self-focusing of the laser radiation in the active medium. [4] This brightness limitation sets in at intensities close to 5×10^9 W/cm^2. [3] In the experiments described below therefore, the energy of the laser pulse was kept at 2–10 J with a pulse duration of 250 psec. The laser beam was focused on the surface of the target with a four-lense objective corrected for a spherical aberration. The size of the focused spot did not exceed 50 μ.

The reflection of the laser ray from the plasma into the solid angle of the objective was measured during the experiment. For pulses of 250 psec duration, the reflection was 1.5–2.5% and, within the limits of measurement accuracy, did not depend on the density of the incident flux. For pulses of 30 psec duration, the reflection varied within limits of 1.5–6%, and a tendency was observed toward a reduction in reflection with increase of the incident-radiation flux density. We note that when the objective was displaced from the position of precise focusing by ±150 μ, no change was observed in the coefficient of reflection. This is at variance with the experiments conducted with nanosecond pulses[5] and with a sequence of USP, [6] utilizing the same objective.

The spectra were recorded with a flat-crystal spectrograph on a photofilm of the UF–VR type. The distance between the plasma and the film was 9 cm. Crystals of LiF($2d=4.04$ Å) and quartz ($2d=6.67$ Å) were used. The inverse dispersion was 0.04 and 0.06 Å/mm respectively. The width of the spectral lines was deter-

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mined by the dimensions of the plasma and did not exceed 100 μ. The wavelengths of unknown lines were calculated from the dispersion curve corresponding to the geometry of the apparatus.

Resonance lines of helium-like ions and their more intensive satellites were employed as reference lines. The wavelength values were those given by Aglitskiĭ *et al.*[7] When there was an insufficient number of lines (Cr, Fe), the dispersion in the measured range was assumed to be constant.

EXPERIMENTAL RESULTS

X-ray spectra of Fe, Cr, Ti, K, Cl, and S ions were obtained in the experiments. Figure 1 shows micrograms of Ti, K, Cl, and S spectra, in which a resonance line and an intercombination line of helium-like ions, together with the satellites corresponding to the transitions $1s^2 2l \rightarrow 1s2l2p$ can be seen. These lines are characteristic of laser-induced-plasma x-ray spectra.[7] Intense lines, corresponding to the 1–2 transitions in ions with a lower multiplicity of ionization (Be-, B-, C-, and N-like)[8] were also observed in our experiments. The 1–2 transition wavelengths of different ions of the same element with a filled L-shell differ little from one another.[9] In our spectrograms, the lines corresponding to such transitions are not resolved. Superposition of these lines, produced a single line ΣK_α whose wavelength coincided with the K_α-line wavelength of the corresponding element.[8] For ions with unfilled L-shells, the shift of the 1–2 transition wavelength is sufficient to resolve the corresponding lines in the spectrograms. Such lines were observed in the spectra of Fe, Cr, and Ti. The spectra of K and Cl were obtained by focusing a laser beam of 4.5 J (Fig. 1b) and 2.2 J (Fig. 1d) average-pulse energy on the surface of a KCl crystal. In general, the structure of these spectra is similar to the structure of the Ti spectrum. However, a comparison

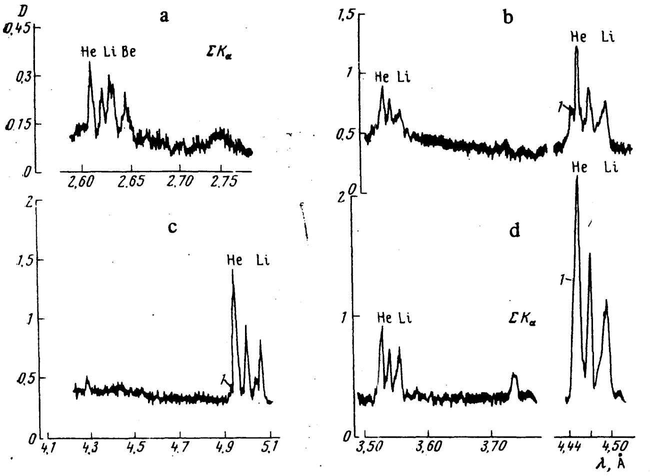

FIG. 1. Micrograms of obtained spectra: a) Ti ($T_e = 1100$ eV, $N_e = 1.5 \cdot 10^{21}$ cm^{-3}); b) KCl ($T_e = 900$ eV, $N_e = 2 \cdot 10^{21}$ cm^{-3}, laser-pulse mean energy 4.5 J); c) S ($T_e = 700$ eV, $N_e = 2 \cdot 10^{21}$ cm^{-3}); d) KCl ($T_e = 400$ eV, $N_e = 3 \cdot 10^{21}$ cm^{-3}, laser-pulse mean energy 2.2 J); 1—shortwave satellite.

TABLE I.

	E^*, J	I_Σ/I_R
Cr	–	0.5
Ti	–	0.17
K	4.5	<0.01
	2.2	0.3
Cl	4.5	<0.01
	2.2	<0.01

*E is the average laser-pulse energy.

of the spectra obtained at different intensities of the laser beam uncovers an interesting property: the intensity ratio I_Σ/I_R of line ΣK_α and the resonance line grows with decreasing energy of the laser pulse. Another characteristic trait of all the obtained spectra is the increase of this ratio with the growth of the atomic number z (see Table I). In particular, the intense line ΣK_α was observed in the Fe spectrum while the resonance line of Fe XXV was absent. In the spectra of Cl and S, on the contrary, the resonance lines of the helium-like ions are the most intense (Fig. 1), while the ΣK_α lines are absent.

The behavior of the lines corresponding to the 1–2 transitions of ions with unfilled L-shells shows the same properties as the ΣK_α lines.

We point out the presence of a shortwave satellite in the resonance line of helium-like ions in the spectra of K, Cl, and S. Earlier, such satellites were observed only when the laser beam was focused onto a depression in the target.[10,11] In our experiments, shortwave satellites were observed when the beam was focused on the surface of a flat target. The shift of the satellite with respect to the resonance line was of the same order as the one observed by V. A. Boĭko *et al.*[10] With a KCl target, however, we observed two shortwave satellites for Cl XVI ($\lambda = 4.433$ Å and $\lambda = 4.437$ Å) and one for K XVIII ($\lambda = 3.523$ Å) when a beam with an average energy of 4.4 J ("strong" flux) struck the target. AE an average energy 2.2 J ("weak" flux), no K XVIII satellite was recorded. Cl XVI had one ($\lambda = 4.440$ Å), but its shift with respect to the resonance line ($\Delta\lambda = 0.004$ Å) was less noticeable than in the case of a "strong" flux ($\Delta\lambda$ - 0.011 Å and $\Delta\lambda = 0.007$ Å).

DETERMINATION OF ELECTRON DENSITY AND PLASMA TEMPERATURE

The plasma-electron temperature T_e was determined in accordance with the well-known method (see for instance C. P. Bhalla *et al.*[12]) using the ratio of the intensities of the dielectron satellites j and k to that of the resonance line. The values of T_e obtained by reducing of the micrograms are shown in the caption of Fig. 1. The spectrograph we utilized in our experiments did not have sufficient resolving power to separate the impact component from the dielectron component in the dielectron structure. The indicated values of T_e must therefore be regarded only as a lower limit.

The plasma-electron density N_e was estimated from the intensity ratio of the intercombination and resonance lines of the helium-like ions.[13] The values of N_e obtained in this manner for K, Cl, and S are marked on the corresponding spectra. In the case of Ti, this method of finding N_e is unsuitable, since its sensitivity region is located at $N_e > 10^{23}$ cm^{-3}. Nor can N_e be determined from the Stark broadening of the lines. However, the analysis of the Ti spectra showed that if nonstationary heating of the plasma is assumed, N_e or T_e can be estimated if one of them is known. Nonstationary heating of the plasma is examined in the next section.

DISCUSSION OF EXPERIMENTAL RESULTS

The most interesting property of the obtained spectra, and the one which requires explanation, is the behavior of the 1–2 transition lines as functions of z and T_e. It is clear that the source of these transition lines for ions with an unfilled L-shell (Be-, B-, C-, and N-like) can only be the plasma. As to the ΣK_α lines, because of the insufficient resolving power of our spectrograph, it is impossible to assign these lines to any specific ions (or set of ions). The K_α lines can be emitted by the target material when bombarded with sufficiently fast electrons. However, such an assumption contradicts the results of experiments conducted with a KCl target, in which the spectra of both elements were obtained simultaneously. The intensity of the potassium ΣK_α line exceeded by no less than 30 times the intensity of the chlorine ΣK_α line. If the source of ΣK_α lines were the target, the intensity of the chlorine-ion ΣK_α line would have to exceed the intensity of the potassium-ion ΣK_α line by approximately five times, since the ionization cross section of the potassium K-shell is smaller than the corresponding chlorine cross section. Thus, it can be concluded that the plasma is also the source of ΣK_α lines.

It is most plausible to explain the presence of lines in the 1–2 transition spectra as follows: in the plasma produced when the laser beam is focused on the target, the electron component heats rapidly (electron-electron thermalization time at $N_e \sim 10^{21}$ cm^{-3} is a few picoseconds). Therefore T_e "follows" the time dependence of the laser-beam intensity. However, a definite time τ_i is needed to establish an equilibrium ion distribution in the ionization multiplicity, corresponding to a given T_e (i.e. to equalize T_z and T_e). The ionization process is therefore quasistationary only if the laser-beam intensity growth is slow enough. With a fast variation in intensity (for example, on the steep pulse front), T_e becomes different from T_z. If a time-integrated spectrum is recorded, its shape must primarily depend on the shape of the heating pulse—on the slope, the front and on the ratio of the rise time to the pulse duration. It is clear that the nonstationarity of the ionization will manifest itself stronger, the steeper the front and the shorter the pulse. It is natural to expect the strongest nonstationarity in the case of ultrashort pulses, when the duration of the entire pulse may be significantly shorter than τ_i.

The value of τ_i in the coronal case depends linearly on electron density N_e. In particular, for Ti with $T_e \approx 1$ keV and $N_e \approx 10^{21}$ cm^{-3} we have $\tau_i \approx 500$ psec. This exceeds the duration of our laser pulse and hence the rise time of the electron temperature in our experiments. The spectra we observed were consequently formed while equilibrium ionization was in progress in the plasma. At the instant of heating, ions of low multiplicity of ionization and a high-temperature electron gas ($T_e > T_z$) are simultaneously present in the plasma. This is accompanied by effective ionization of ion K-shells by the electrons and leads to the emission of the corresponding lines.

The value of magnitude τ_i grows with increasing z and decreasing in T_e.[1)] Naturally, as τ_i grows longer the sojourn of low-multiplicity ions in the plasma also increases in duration, i.e., the intensity of the ΣK_α line must increase. The behavior of lines which correspond to 1–2 transitions in ions with filled L-shells is similarly explained.

The duration of ionization can be qualitatively described by a system of differential equations. We assume that:

1) T_e reaches its maximum value instantly and does not vary during the laser-pulse;

2) N_e is also constant during the laser-pulse;

3) the ionization balance is secured by impact ionization and photorecombination.

With these assumptions, the equations take the form

$$\begin{aligned} \dot N_{\rm I} &= -a_{\rm I}N_{\rm I} + b_{\rm II}N_{\rm II}, \\ \dot N_{\rm II} &= +a_{\rm I}N_{\rm I} + b_{\rm III}N_{\rm III} - (b_{\rm II}+a_{\rm II})N_{\rm II}, \\ &\cdots\cdots\cdots \\ \dot N_K &= a_{K-1}N_{K-1} - b_K N_K, \end{aligned} \tag{1}$$

where N_K is concentration of the ion with the spectroscopic symbol K, and a_K and b_K are respectively the ionization and recombination coefficients for the ion K (their values were calculated from the equations published by Brukhnevitch *et al.*[16]).

An electronic computer was employed in solving system (1). The initial conditions were as follows:

$$N_K = \begin{cases} 1, & K=1 \\ 0, & K \neq 1 \end{cases}. \tag{2}$$

Figure 2 shows the results of such a calculation for Ti with $N_e = 10^{21}$ cm^{-3} and illustrates the nonstationarity of the plasma-ionization process under the conditions of our experiments.

On the basis of such a qualitative description, it is possible to estimate N_e in the case of Ti. The intensity of the spectral line which corresponds to the 1–2 transition of a Be-like ion is determined by the relation

$$I_{\rm Be} = \frac{A_r}{A_r + A_a} N_e \int_0^\tau (\langle v\sigma_{\rm Be}\rangle N_{\rm Be} + C_d N_{\rm Li})\, dt, \tag{3}$$

where τ is the hot-plasma lifetime, C_d is the coefficient of the dielectron recombination, $\langle v\sigma_{\rm Be}\rangle$ is the rate of impact activation, and A_r and A_a are the probabilities of radiative decay and autoionization.

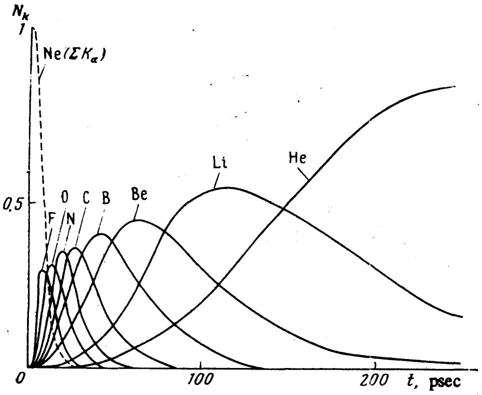

FIG. 2. Time dependence of ionization (results of solution of system (1) for Ti); $T_e = 1000$ eV.

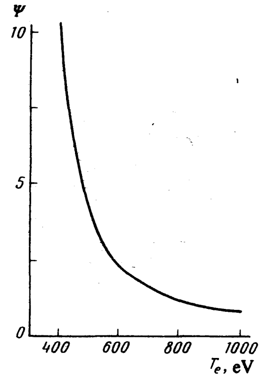

FIG. 3.

The resonance-line intensity of an He-like ion is

$$I_R = N_e \langle v\sigma \rangle_{1s-2p} \int_0^\tau N_{He}\, dt, \tag{4}$$

where N_{He} is the concentration of He-like ions and $\langle v\sigma \rangle_{1s-2p}$ is the average cross section of the $1s-2p$ impact excitation.

When the plasma is heated with ultrashort pulses,[15,16] the duration of the plasma x-ray pulse (i.e., the hot plasma lifetime) coincides with the duration of the heating pulse, $\tau = \tau_{pul}$. In solving system (1), the values of the integrals in (4) and (3) were estimated.

We examine the relation

$$\frac{I_{Be}}{I_R} = A_r \int_0^{\tau_{pul}} (\langle v\sigma_{Be} \rangle N_{Be} + C_d N_{Li})\, dt \left[(A_r + A_a) \int_0^{\tau_{pul}} \langle v\sigma \rangle_{1s-2p} N_{He}\, dt \right]^{-1}. \tag{5}$$

For a constant value of T_e, this equation depends only on N_e and it can therefore be utilized to estimate N_e. The atomic constants necessary for the estimate were calculated from the equations published by Vaĭnshteĭn *et al.*[17] There are no published data for the autoionization probabilities A_a of the Be-like Ti ion. It was estimated that $A_a \approx 10^{13}$ sec^{-1} and hence $N_e = 2.10^{21}$ cm^{-3}.

When the target was KCl, the electron temperature T_e was also estimated from the ratio of the resonance-line intensities of the He-like K and Cl ions:

$$\Psi = I_{R_{Cl}}/I_{R_K} = \langle v\sigma \rangle_{1s-2p\,Cl} \int_0^{\tau_{pul}} N_{HeCl}\, dt \times \left[\langle v\sigma \rangle_{1s-2p\,K} \int N_{HeK}\, dt \right]^{-1}. \tag{6}$$

The dependence of this ratio on T_e is shown in Fig. 3 for $N_e = 10^{21}$ cm^{-3}. The obtained T_e proved to be 900 eV for a laser-pulse mean energy 4.5 J, and 500 eV for a mean energy 2.2 J.

CONCLUSION

The experiments have shown that when plasma is heated by a subnanosecond laser pulse, the plasma x-ray spectra contain lines emitted by ions of comparatively low ionization multiplicity besides the lines emitted by the multiply-charged ions, although the electron temperature reaches ~1 keV and the electron density ~10^{21} cm^{-3}. Such a spectrum is caused by the nonstationarity of the ionization process: conditions are created in the plasma under which electrons have the time to become quickly heated during the pulse, while the ions do not have the time to reach the ionization level that corresponds to the electron temperature.

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1)The growth of τ_i with increasing z can also cause nonstationary ionization when the plasma is heated by a nanosecond laser-pulse (see the Fe spectra studied by Boĭko *et al.*[14]).

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Langmuir turbulence and dissipation of high-frequency energy

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We construct a theory of three-dimensional Langmuir turbulence. We give the turbulence spectra in the inertial and the absorption ranges and we analyze the role of possible absorption mechanisms for the short-wavelength plasmons. We find the effective collision frequency which characterizes the power dissipated from the pumping wave. We study the effect of the build-up of short-wavelength acoustic oscillations on the turbulence. We solve the problem of the dynamics of plasma turbulence excited by an electromagnetic wave with a frequency differing from the plasma frequency.

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§1. INTRODUCTION

The interest in the problem of strong turbulence is to a large extent connected with practical applications—the necessity for establishing effective collisionless mechanisms for energy dissipation when one uses lasers of beams to initiate a thermonuclear reaction. On the other hand, at the present there is no sufficiently consistent formulation of a strong turbulence theory which would enable us to connect the collapse of an isolated caviton with plasmons as the microscopic manifestation of the modulational instability with such macroscopic characteristics as the power dissipated from the pumping wave, the hot-particle distribution function, and others.

The idea of the collapse as the non-linear stage, discovered by Vedenov and Rudakov,[1] of the modulational instability of Langmuir waves is due to Zakharov.[2] He showed that the localization of the plasma waves caused by the modulational instability ultimately can lead to the formation of cavitons (regions of lowered plasma density with plasmons trapped in them) collapsing to dimensions where some mechanism for the dissipation of the plasmon energy is switched on.

One of the authors of the present paper (see, e.g., Ref. 3) suggested simple considerations which could be used to study the possibility for collapse depending on the number of dimensions of the caviton. These considerations are based on the relation between the density well depth and the wavelength of the plasmons trapped in them:

$$|\delta n|/n_0 \sim k^2\lambda_D^2 \qquad (1.1)$$

(the kinetic energy of the trapped plasmons is of the order of the potential energy), and on the condition that the plasmon number in each separate caviton is constant:

$$\frac{1}{4\pi\omega_p}\int d\mathbf{r}|\mathbf{E}|^2=\text{const.} \qquad (1.2)$$

As the depth of the density modulation in the cavitons is usually small ($\delta n \ll n_0$), $\omega_p \approx$ const and it follows from the last condition that the radiation pressure in the center of the caviton leading to a displacement of the plasma and to collapse will during the collapse increase inversely proportionally to its volume $|E|^2 \propto l^{-s}$($l \sim 1/k$ is the characteristic size of the caviton, $s = 1, 2, 3$ is its dimensionality). For collapse, at the same time, one must overcome the pressure of the displaced plasma δnT which, according to (1.1), increases as l^{-2}. Hence it follows that the one-dimensional case is a special one—for some l the balance between the pressures and the collapse necessarily ceases. When $s = 2$ the possibility of a collapse depends on the initial conditions—if initially the high-frequency pressure in the caviton is larger than the gas-kinetic pressure, collapse will not set in at a later stage. And finally, in the three-dimensional case collapse is inevitable.

Recently self-similar solutions describing the collapse of a caviton have been obtained[4,5] and the approach to the self-similar solution has been considered using a computer (see Ref. 5) so that notwithstanding the absence of a rigorous mathematical proof the fact of the collapse of an isolated caviton with plasmons is indisputable.

Our aim in the present paper is to make the transition

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