Observation of intensity anomalies at 58–78 Å in Cl VII transitions in two-stage plasma heating by ultrashort laser pulses

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An anomalous increase was observed experimentally in the intensities of a number of lines in the 58–78 Å range, corresponding to transitions of the Cl VII ion from autoionization states.

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1. A laser plasma is one of the most suitable media with which to obtain amplification in the far vacuum ultraviolet and soft x-ray regions,[1] and several concrete schemes have been proposed to excite multiply charged ions for this purpose (see the review[2]). In particular, by using short laser pulses

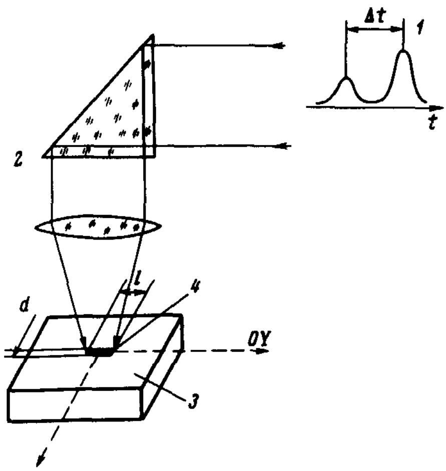

FIG. 1. Experimental setup. 1) Time structure of laser radiation, 2) radiation-focusing system, 3) KCl target, 4) plasma pinch with indication of the spectrum observation directions *OX* and *OY*.

it is possible to realize the so called two-stage plasma heating, wherein the first laser pulse produces a plasma with ions of the required ionization multiplicity, while the second pulse, which is ultrashort, produces additional heating of the plasma electrons.[3,4] We report here observation of anomalies in the intensities of the emission lines of Cl VII in the course of this heating.

2. We used in the experiments a laser setup with an AlYG driving laser and a multistage neodymium-glass amplifier.[5] The two-stage heating was produced by using two ultrashort pulses (USP) of 0.25 nsec duration each. The interval Δt between pulses could be varied from 0 to 1.5 nsec. The energy of the second pulse was 3.2 times larger than that of the first. The combined energy of the pulses fluctuated between 6 and 8 J. The laser radiation was focused with a special lens on a KCl target to produce an elongated focal spot of width $d = 0.1$ mm and length $l = 1.5$ mm.

The plasma emission spectra in the 50—800 Å range were registered with a

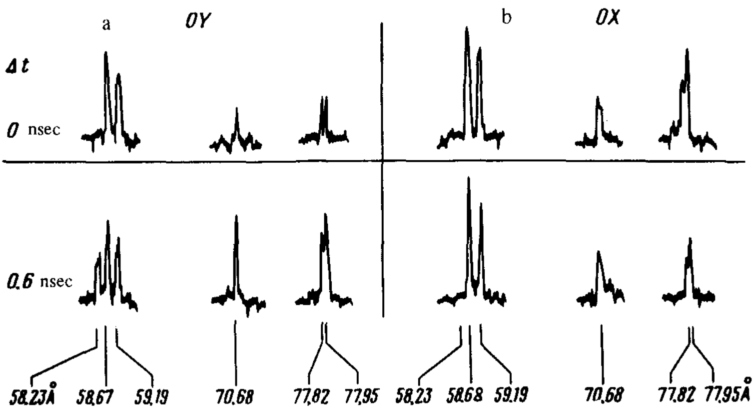

FIG. 2. Density patterns of spectra at different values of Δt in the case of longitudinal (a) and transverse (b) observation.

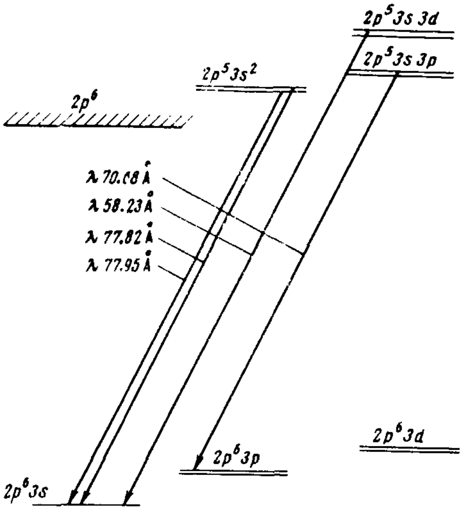

FIG. 3. Level and transition scheme with anomalous intensity of Cl VII emission lines.

DFS-6 spectrograph on a UF-4 photographic film. The spectra were observed along and across the plasma-pinch axis, as shown in Fig. 1. The distance from the plasma to the spectrograph slit was 40 mm, and the width at the slit was 6 μ; the height of the spectral lines was determined by the spectrograph cassette and amounted to 1 cm, equivalent to an observation angle ~ 0.03 rad. Each spectrum was the result of 10 laser flashes.

3. Observation along the plasma pinch axis revealed an increase in the intensities of the lines $\lambda = 58.23$, 70.68, 77.82, and 77.95 Å; the increase depended on Δt. Figure 2 shows the corresponding sections of the spectra for different values of Δt, as observed along (Fig. 2(a)) and across (Fig. 2(b)) the plasma-pinch axis. It is seen from Fig. 2 that the relative intensities of the resonant Cl VIII transition ($2s^2 2p^6 - 2s^2 2p^5 3s$, $\lambda = 58.67$ Å; $\lambda = 59.19$ Å) were independent of the observation direction. They were therefore used to normalize the intensities of the lines with the anomalous behavior.

At $\Delta t = 0$, the line $\lambda = 58.23$ Å was not observed at all. The intensities of the lines $\lambda = 70.68$ Å and $\lambda = 77.82$ Å were practically independent of the observation direction. The intensity of the $\lambda = 77.95$ Å line observed across the pinch axis is 1.3 times larger than in the case of longitudinal observation. At $\Delta t = 0.6$ nsec, the intensities of these lines increased when observed longitudinally. The largest increase occurred for the $\lambda = 58.23$ Å line. Its intensity in longitudinal observation was not less than five times larger than in transverse observation.

Further increase of Δt revealed a tendency of these line intensities to become equalized in the two directions (the intensity ratio for $\lambda = 58.23$ Å at $\Delta t = 1$ nsec was 1.5).

4. Additional experiments were performed with the plasma heated by a single pulse of 1.2 nsec duration. The laser beam was focused into a spot with $l = 1.5$ mm or with $l = 3$ mm, and the radiation flux density on the target was the same in both cases ($\sim 10^{13}$ W/cm^2). In these experiments, we compared only the spec-

tra observed in the longitudinal direction. As l was increased from 1.5 to 3 mm, the line $\lambda = 58.23$ Å appeared in the spectrum (its relative intensity increased by not less than five times), and the relative intensities of the other lines that exhibited the anomalies in two-stage heating increased twofold.

5. Identification of the lines with anomalous behavior has shown that they correspond to transitions from doubly excited autoionization states of the Cl VII ion $(2s^2 2p^5 3l3l')$ to a state of the type $2s^3 2p^6 3l'$ (Fig. 3).

6. The anomalous behavior of the line intensities can be due either to absorption in the external plasma layers, or to amplification along the plasma-pinch axis. It is quite difficult to offer an unequivocal interpretation, since there are no data on the spatial distributions of the electrons and ions in the plasma pinch. The absorption of the radiation by the Cl VII ions in the lower states should have led to equalization of the intensities in the components of the doublet $2s^2 2p^6 3s \rightarrow 2s^2 2p^5 3s^2$. At $\Delta t = 0.6$ nsec, however, the intensity ratio of these lines did not depend on the observation direction. It is difficult to explain this fact if strong absorption is assumed.

The fact that the lines with the anomalous behavior have a higher intensity when the plasma pinch is made longer is also difficult to explain within the framework of the absorption mechanism. On the other hand, the assumption that amplification takes place can explain the anomalous behavior of the intensities of these lines. Under this assumption, the gain for the $\lambda = 58.23$ Å lines should be ~ 10 cm^{-1}.

A conclusive explanation of the mechanism that produces the observed intensity anomalies calls for more experiments with lasers of higher power.

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