Observation of plasma satellites of x-ray lines of multiply charged ions and measurement of the density ~ 10^{23} in conical cumulation of a laser plasma

V. A. Boĭko, O. N. Krokhin, S. A. Pikuz, and A. Ya. Faenov

P. N. Lebedev Physics Institute, USSR Academy of Sciences
(Submitted June 10, 1974)
ZhETF Pis. Red. **20**, 115–119 (July 20, 1974)

We observed the presence of short-wave satellites of the resonance lines of the heliumlike ions Mg XI, Al XII, P XIV, and S XV in conical cumulation of a laser plasma. For composite targets with 80% CD_2+20% P, in the case of cumulation of a plasma in a conical depression, we registered in 30% of the laser flashes thermal neutrons with a total ~10^3 per pulse. A special experiment, in which the registration was carried out simultaneously by three spectrographs in three projections, has shown that the form of the spectrum does not depend on the registration direction. The presence of such a short-wave satellite is interpreted as emission of a plasma satellite shifted by an amount equal to the Langmuir frequency relative to the frequency of the forbidden transition $1s^{2\prime}S_0$-$1s2s'S_0$. This interpretation gives for the maximum electron density in the cumulated plasma a value from 6×10^{22} to 1.8×10^{23}.

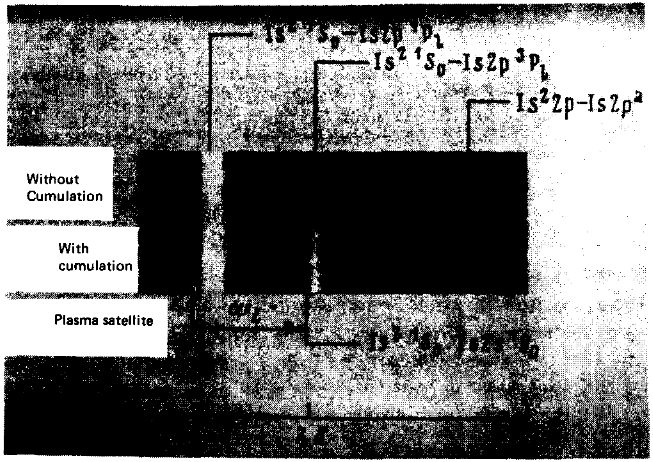
An important place in the problem of heating a thermonuclear laser plasma[1] is occupied by the development of procedures for the diagnostics of plasma densities in the range 10^{21}—10^{26}. There are at present no published reports of direct measurement of plasma densities higher than 10^{20}. As noted in[2,3], the diagnostics of a laser plasma at solid-state densities and higher can be carried out by x-ray spectroscopy methods using the lines of multiply-charged ions.

We have investigated the x-ray spectra of a laser plasma produced by focusing the heating radiation, with a flux density $q\sim5\times10^{14}$ W/cm^2, both on a level surface of a solid target and in a conical depression. We used both homogeneous and composite targets (see the table). For a target of 80% CD_2+20% P, in the case of plasma cumulation in a conical depression, in analogy with the data of[4], we registered thermal neutrons in approximately 30% of the laser flashes; the total number of neutrons per pulse was ~10^3. The figure shows characteristic spectrograms obtained after 5—15 laser flashes, as functions of the charge of the target-element nucleus. The heliumlike-ion spectra on these spectrograms were identified on the basis of the data of[5,6]. A remarkable feature of the spectra obtained in the case of plasma cumulation is the presence of *short-wave* satellites of the resonance lines of the Mg XI, Al XII, P XIV, and S XV ions (unlike the long-wave satellites due to transitions from doubly-excited levels of lithiumlike ions—see, e.g., [7]). The absence of short-wave satellites in experiments without cumulation offers unambiguous proof that the indicated satellites are due not to apparatus effects but to plasma radiation.

A possible interpretation of this effect might be the presence, in the plasma, of a cumulative jet directed along the axis of the conical depression and containing a fraction of the radiating heliumlike ions. The translational motion of these ions could lead to a double shift of resonance line (with $\Delta\lambda/\lambda\sim10^{-3}$, corresponding to a velocity ~3×10^7 cm/sec, which is typical of a laser plasma). A special experiment, however, in which we registered the spectra in three projections simultaneously by three spectrographs, has shown that the form of the spectrum does not depend on the registration direction.

The action of the surrounding plasma particles on an ion in an excited state can lead to the emission of plasma satellites that are shifted relative to the frequency of the forbidden transition by an amount equal to the Langmuir frequency $\omega_L=\sqrt{4\pi e^2N_e/m}$.[8] The discussion of the possibility of measuring the electron density on a laser plasma by means of such plasma satellites is contained in[3]. In our case of heliumlike ions, such a forbidden transition is $1s2s^1S_0\to1s^{21}S_1$, the frequency of which is close to the frequency of the $1s2p^3P_1\to1s^{21}S_0$ intercombination line and is marked for Mg XI in the figure. In the transition $1s2s^1S_0\to1s^{21}S_0$ with excitation of a plasma oscillations, either a Stokes or an anti-Stokes satellite can be emitted. The short-wave satellite of the resonance line (see the figure and the table)

Target	Ion	$1s\,2p\,^1P_1\to1s^{2\,1}S_0$ λ_1, Å (exp.)	$1s\,2s\,^1S_0\to1s^{2\,1}S_0$ λ_2, Å$_{theor}$	Plasma satellite λ_3, Å (exp.)	$\Delta\lambda=\lambda_2-\lambda_3$ Å	N_e, cm^{-3}
Mg	Mg XI	9.1682	9.2252	9.1602	0.0650	$6.4\cdot10^{22}$
Al	Al XII	7.7565	7.8015	7.7490	0.0525	$8.25\cdot10^{22}$
P	P XIV	5.7591	5.7885	5.7528	0.0357	$1.25\cdot10^{23}$
S	S XV	5.0374	5.0636	5.0311	0.0325	$1.76\cdot10^{23}$
80% CD_2 + 20% P	P XIV	5.7591	5.7885	5.7534	0.0351	$1.1\cdot10^{23}$



should be ascribed to the anti-Stokes satellite. Separation of the Stokes satellite is difficult, since it is located in the structure of the dielectronic satellites. In addition, the anti-Stokes satellite has a much higher intensity, because of the frequency resonance: $\omega_L \approx (1s2s\,^1S_0 - 1s2p\,^1P_1)$.

The table lists the experimental wavelengths of the resonance lines λ_1, of the plasma satellites λ_3, the theoretical wavelengths of the forbidden lines λ_2,[1)] the difference $\Delta\lambda = \lambda_2 - \lambda_3$, and also the electron density N_e calculated under the assumption that $\Delta\lambda$ corresponds to the Langmuir frequency ω_L. The resonance condition "picks out" from the density profile in the cumulating plasma the values of N_e listed in the table, which are apparently close to the maximal values. The electron temperature, determined from the measured ratios of the intensities of the resonance lines and of the dielectronic satellites, is ~ 0. 5 keV. The electron pressure $p = N_e kT$ reaches in this case a value 8×10^7 atm, which is several times larger than the pressure on the surface of the target in the absence of cumulation, determined in[9] by measuring the momentum of the expanding plasma. The value of N_e determined from the ratio of the intensities of the resonance and intercombination lines (see[9]) yields in our case for CI XVI a value $\sim 10^{21}$, which is apparently averaged over volume and over time.

The authors thank N. G. Basov for interest in the work, Yu. V. Afanas'ev, A. V. Vinogradov, E. G. Gamaliya, V. B. Rozanov, I. I. Sobel'man, and E. A. Yukov for useful discussions.

[1)]The authors are grateful to L. A. Vaĭnshteĭn for supplying the theoretical wavelengths of the forbidden lines.

[1]N. G. Basov and O. N. Krokhin, Zh. Eksp. Teor. Fiz. **46**, 171 (1964) [Sov. Phys.-JETP **19**, 123 (1964)].
[2]V. A. Boiko, O. N. Krokhin, and G. V. Sklizkov, FIAN Preprint No. 121, 1972; Trudy FIAN, 76; Lazery i ikh primenenie (Lasers and their applications), in press.
[3]A. V. Vinogradov, I. I. Sobel'man, and E. A. Yukov, FIAN Preprint No. 173, 1973; Kvantovaya élektronika **1**, 579 (1974) [Sov. J. Quant. Electr. **4**, 322 (1974)].
[4]N. G. Basov, V. A. Boĭko, S. M. Zakharov, O. N. Krokhin, Yu. A. Mikhaĭlov, G. V. Sklizkov, and S. I. Fedotov, ZhETF Pis. Red. **18**, 314 (1973) [JETP Lett. **18**, 184 (1973)].
[5]E. V. Aglitskiĭ, V. A. Boĭko, L. A. Vaĭnshteĭn, S. M. Zakharov, O. N. Krokhin, and G. V. Sklizkov, Opt. Spektrosk. **35**, 963 (1973).
[6]E. V. Aglitskiĭ, V. A. Boĭko, S. M. Zakharov, I. A. Konoplev, S. A. Pikuz, and A. Ya. Faenov, FIAN Preprint No. 163, 1973.
[7]A. H. Gabriel and C. Jordan, Nature **221**, 947 (1969).
[8]H. J. Kunze and H. R. Griem, Phys. Rev. Lett. **21**, 1048 (1969).
[9]V. A. Boĭko, Yu. A. Drozhbin, S. M. Zakharov, O. N. Krokhin, V. A. Nikulin, S. A. Pikuz, G. V. Sklizkov, A. Ya. Faenov, Yu. V. Chertov, and V. A. Yakovlev, FIAN Preprint No. 77, 1973.