Anomalous intensities of the resonance lines of Ne-like ions in plasma produced by a picoscond laser pulse

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Anomalous structure of the intensities of the spectral lines of the Ne-like ions CuXX and GeXXIII, emitted by a plasma produced by picosecond laser pulses with flux densities of up to 2×10^{18} W/cm^2, was recorded for the first time. It is shown that the maximum of the emission spectra of these ions occurs from the region of the plasma where the density is much higher than the critical density for the wavelength of the heating laser radiation. © *1995 American Institute of Physics.*

The resonance series $2s^{k1}2p^{k2}nl \rightarrow 2s^2 2p^6\ {}^1S_0$ $(k1+k2=7)$ of multiply charged Ne-like ions observed in the plasma of different laboratory and astrophysical objects ordinarily contain for each n seven spectral lines, designated as nA, nB, ..., nG (in order of increasing wavelength), with comparable intensities (see, for example, the review in Ref. 1). It is easy to see that this ratio of the line intensities is valid only under coronal or close-to-coronal conditions, when the relative intensities of the spectral lines are determined by the rates of excitation of the corresponding ion levels from the ground state by electron impact. In the opposite case of a dense plasma with a Boltzmann distribution of the populations of the excited states, the relative intensities of some of their lines should become very low. For example, the $3F$ and $3G$ lines (for ions with charge $z\sim 20$) in a superdense plasma should be 20–30 times weaker than the $3C$ and $3D$ lines, since their radiation probabilities are lower by the same factor and the statistical weights of all levels of the resonance series are identical. Apparently, this fact was first pointed out in Ref. 2 , but thus far such anomalous intensity ratios for the lines of multiply charged Ne-like ions have not been observed. This is connected with the fact that the transition from the coronal to a Boltzmann distribution occurs at very high plasma densities $N_e \sim 10^{12}\cdot Z^7$ cm^{-3} and even a dense laser plasma for ions with $Z \geqslant 20$ is described quite well by the coronal model.

In the present paper we report the first observation of the anomalous structure of the intensities of the transitions $n=3 \rightarrow n'=2$ in the Ne-like ions CuXX and GeXXIII emitted by a superdense plasma heated by picosecond laser pulses.

The experiments were conducted on a laser setup at the Max Born Institute in Germany. This setup consists of a neodymium-glass CPA laser operating on the principle of amplification of a phase-modulated pulse and subsequent compression of the pulse

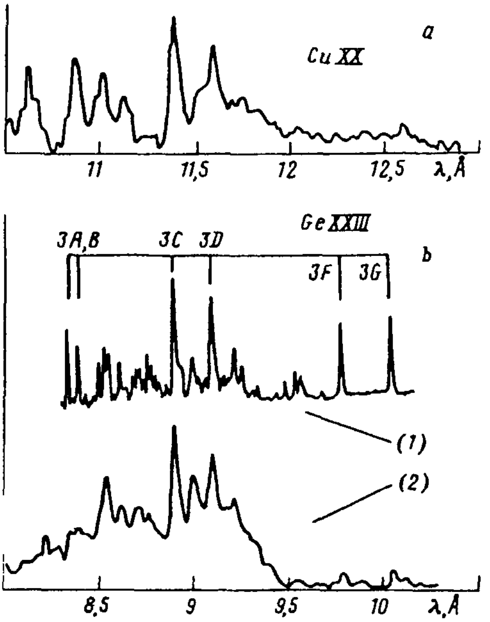

FIG. 1. Emission spectra of copper (a) and germanium (b) plasma produced by picosecond laser pulses (a, b — densitometer trace 2) and nanosecond pulses (b — densitometer trace 1). The standard designations are used for the spectral lines of Ne-like ions: $3A$, $3B$ ($2s2p^63p\ ^{1,3}P_1-2s^22p^6\ ^1S_0$), $3C$ ($2s^22p^53d\ ^1P_1-2s^22p^6\ ^1S_0$), $3D$ ($2s^22p^53d^3D_1-2s^22p^6\ ^1S_0$), $3F$, $3G$ ($2s^22p^53s\ ^{1,3}P_1-2s^22p^6\ ^1S_0$).

with a stretcher on diffraction gratings. A more detailed description is given in Ref. 3 . To increase the contrast and shorten the leading edge of the pulse, a cell containing a saturating absorber (Kodak-9860 dye solution in dichloroethane) was installed after the compressor. This improved the contrast of the short pulse with respect to the amplified spontaneous radiation up to 10^{10} (Ref. 4). The laser pulse at the exit of the setup therefore had an energy of up to 1 J with a pulse duration of 2 ps at half-height.

To produce the plasma, an aspherical $f/2$ lens was used to focus the laser beam onto the surface of massive flat Cu and Ge targets. Under the optimal focusing conditions $\sim 40\%$ of the radiation was concentrated in a 5-μm-diameter spot, so that the flux density of the heating radiation at the target was equal to $\sim 2\times 10^{18}$ W/cm^2. The x-ray spectra of the plasma in the range 8–13 Å were recorded with a spectrograph with a flat CsAP crystal and a FSSR-1D focusing spectrograph with a mica crystal, curved along a sphere with a radius[5] $R=100$ mm. A RAR-2495 photographic film was used. The calibration curves for the film were taken from Ref. 6 .

The spectra obtained in the present work are shown in Fig. 1. For comparison the spectrum of a Ge plasma observed in the experiments of Ref. 7 on the heating of plasma with nanosecond pulses are also shown in Fig. 1.

To interpret the experimental results, we calculated the kinetics of the Ne-like ion GeXXIII in a dense, high-temperature plasma. The quasistationary radiation-collisional

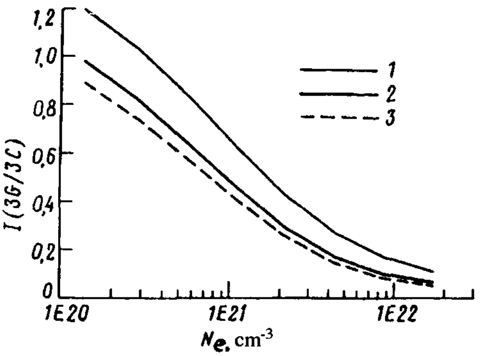

FIG. 2. Intensity ratio $I(3G)/I(3C)$ of the lines of the Ne-like ion GeXXIII at the temperatures $T_e = 265$ eV (curve 1), $T_e = 529$ eV (curve 2), and $T_e = 794$ eV (curve 3).

kinetic model employed was similar to that described in Ref. 8. It included levels belonging to the configurations $1s^2 2s^2 2p^6$, $1s^2 2s^2 2p^5 nl$, $1s^2 2s 2p^6 nl$, $1s^2 2s^2 2p^5$, and $1s^2 2s 2p^6$ with $n = 3-6$. The fine structure of the levels with $n = 3$ was taken into account; levels with $n = 4$ were assumed to be degenerate with respect to the total angular momentum; and, levels with $n = 5$ and 6 were assumed to be degenerate with respect to the total and orbital angular momenta. All radiative transitions between the indicated states and all transistions produced by collisions with electrons (i.e., excitation, deexcitation, ionization, triple recombination, and photorecombination) were taken into account in the kinetic matrix. The result of the kinetic calculation were the relative intensities of the lines $3A-3G$ for a plasma with different values of N_e and T_e. For example, the computed dependences of the intensity ratios $I(3G)/I(3C)$ for the $3G$ and $3C$ lines as a function of the electron density of the plasma are shown in Fig. 2. It is evident from this figure that this intensity ratio depends mainly on N_e and that the transition from the coronal to the Boltzmann distribution occurs in the region $N_e \sim 10^{21} - 10^{22}$ cm^{-3}. The curve obtained can be used to estimate the electron density of the plasma. For example, comparing for the spectrum obtained by heating the plasma with a nanosecond laser pulse (see Fig. 1b, densitometer trace *1*) the experimental value of the intensity ratio $I(3G)/I(3C)$ with the data in Fig. 2 gives the average value $N_e \cong (3-4) \times 10^{20}$ cm^{-3}.

To model the spectrum obtained with picosecond heating (Fig. 1b, densitometer trace *2*), we also calculated the emission spectrum of the dielectron satellites produced in the radiative decay of the levels $1s^2 2s^{k1} 2p^{k2} 3l_1 3l_2$ $(k1 + k2 = 7)$ of the Na-like GeXXII ion which lie above the ionization limit of this ion. In contrast to the lines of the Ne-like GeXXIII, the relative intensities of the dielectron satellites, the strongest of which lie in the region $\lambda \sim 9-9.3$ Å (i.e., to the right of the line $3C$), depends mainly on the electronic temperature of the plasma, and the values of N_e and T_e can be determined simultaneously by comparing the total computed and experimental spectra. Specifically, for the emission spectrum of a picosecond laser plasma which we observed, the best agreement between the experimental data and the calculations corresponded to the values $N_e = 10^{22}$ cm^{-3} and $T_e = 310$ eV (see Fig. 3). It should be noted that several lines ob-

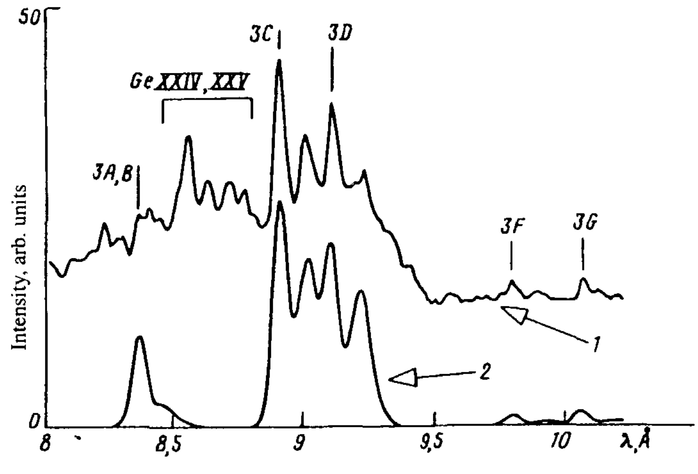

FIG. 3. Emission spectrum of a germanium picosecond laser plasma in the region 8–10.2 Å. Curve 1 — experiment; curve 2 — calculations (without the lines of the F- and O-like ions GeXXIV, XXV).

served in the region $\lambda \cong 8.5-8.8$ Å belong to F- and O-like ions GeXXIV and GeXXV, for which a calculation was not performed.

The spectra recorded without time resolution can be used to estimate only the average value of the plasma parameters, and the electron density $N_e = 10^{22}$ cm^{-3} is not the maximum density $N_e^{\max}$ which exists during plasma evolution. Let us assume that $I(3G)/I(3C) = \varphi(N_e)$, where $\varphi(N_e)$ is the decreasing function shown in Fig. 2. For the intensity ratio $I^{\text{obs}}(3G)/I^{\text{obs}}(3C)$ recorded on the film we then have

$$I^{\text{obs}}(3G)/I^{\text{obs}}(3C) = \int\int \varphi(N_e) I(3C)\,dV\,dt \Bigg/ \int\int I(3C)\,dV\,dt, \tag{1}$$

where the integration is performed over the plasma lifetime and over the spatial region covered by the spectrograph. It follows from Eq. (1) that

$$I^{\text{obs}}(3G)/I^{\text{obs}}(3C) = \varphi(N_e^{\max}) \int\int \frac{\varphi(N_e)}{\varphi(N_e^{\max})} I(3C)\,dV\,dt \Bigg/ \int\int I(3C)\,dV\,dt > \varphi(N_e^{\max}), \tag{2}$$

since $\varphi(N_e)/\varphi(N_e^{\max}) \geqslant 1$ in the entire region of integration, and therefore the value of N_e^{obs} determined by the condition $I^{\text{obs}}(3G)/I^{\text{obs}}(3C) = \varphi(N_e^{\text{obs}})$ satisfies the relation $N_e^{\text{obs}} < N_e^{\max}$.

Since the measured average value of the electron density is higher than the critical plasma density for the wavelength of the heating radiation, $N_{e\text{cr}} \sim 10^{21}$ cm^{-3}, this means that the maximum of the emission spectra of the L-ions (i.e., ions for which the L-shell is the ground-state shell) occurs from the region of the plasma located between the critical surface and the surface of the solid. We obtained a similar result previously for the

K spectra of silicon ions in a plasma heated with subpicosecond laser pulses.[9] This result is in good qualitative agreement with the hydrodynamic calculations performed in Ref. 4.

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