X-ray spectrum of He-like chromium in a laboratory plasma

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X-ray spectra of He-like chromium are obtained with the aid of a light amplifier in the T-10 tokamak facility under various plasma heating conditions. The experimentally observed wavelengths of the intense lines agree well with the theoretical values. The electron temperature of the plasma is estimated from the relative line intensities. The results agree with the data obtained by other methods.

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1. INTRODUCTION

Interest in the spectra of highly ionized atoms was initially connected almost exclusively with investigations of astronomic objects and phenomena (solar corona, chromosphere flares). Progress in controlled thermonuclear fusion has made it clear that a study of the spectra of multiply charged impurity ions can be of great importance for the determination of the state of a hot laboratory plasma. The traditional connection between plasma physics in outer space and in the laboratory has manifested itself here in full measure (see the recent interesting and comprehensive reviews[1]). Incidentally, a correspondence between the spectra of the chromosphere at the instant of a solar flare and the spectra of a pulsed discharge in hydrogen, at a current ~0.5 MA at the maximum, was observed already two decades ago.[2] The Stark broadening of the Balmer lines was tremendous in both cases (the experiments were restricted then only to the visible region of the spectrum).

The spectra of highly ionized atoms are much richer in lines than the analogous spectra of neutral atoms. They contain series of satellite lines accompanying the main transitions. By comparing the line intensities it is possible to determine such plasma parameters as the electron temperature and density, the ionization state, and the deviation of the electron velocities from a Maxwellian distribution. Interest has therefore increased in theoretical calculations of the spectra[3-5] and in their experimental study.[6,7] Applications of spectral methods, particularly in the diagnostics of plasma by using thermonuclear facilities such as tokamaks,[8,9] are being extensively discussed in the literature. Bitter *et al.*[10] have described the measurement of the ion temperature by determining the Doppler broadening of the resonance line in the spectrum of Fe-XXV. Such measurements are important because other methods used to measure ion temperature become apparently less reliable in the case of large installations.

Elements such as Ti, Cr, Fe, Ni, and Mo are frequently present as impurities in the hydrogen plasma of a tokamak and enter the plasma volume from the diaphragm or from the walls of the toroidal chamber. Since the appearance of each highly ionized state for any element is connected with a definite temperature, it becomes possible to measure the plasma parameters locally. More accurately speaking, in the case of the distribution of ionized atoms in a plasma pinch, it is possible to determine the radial distribution of the temperatures from the narrow radiating sheaths, bypassing the inaccurate operation of the Abelian inversion.

We present in this paper the results of reduction of the spectrum of the helium-like chromium Cr-XXIII, obtained in experiments on the T-10 tokamak. The same facility was used earlier to obtain the spectra of highly ionized chromium with a smaller resolution but in a wider spectral band.[11]

2. TECHNIQUE

The measurements were performed with a large-dispersion x-ray spectrograph. The dispersive element was developed by M. M. Stepanenko with V. A. Rantsev-Kartinov participating. It was a plate measuring 50 × 20 mm, cut of artificial quartz crystal along the $13\bar{4}0$ plane (distance between planes $d = 1.1802$ Å) and bent to a radius of 50 cm. This plate was placed in a hermetically sealed chamber filled with helium. The x rays were admitted into the chamber through windows of thin organic film.[12]

The spectra were recorded by photography. To increase the sensitivity, the x rays were converted into visible light, whose brightness was enhanced with an electron-optical light amplifier. The converter was the K-51 luminor, based on zinc sulfide. The luminor was coated on the end surface of a flexible optical light pipe. The thickness of the luminescent layer (10 mg/cm^2) was chosen such that the x rays were absorbed in it completely. The concerter-screen produced in this manner measured 20 × 4 mm. The light pipe was secured on the spectrograph chamber and the x-ray image of the spectrum was focused on its end face. The other end face of the light pipe was in contact with the light amplifier which had fiber-optics windows.

The employed light amplifier with microchannel plate enhanced the brightness of the spectrum by more than 10^4 times while maintaining a rather high spatial resolution (~30 lines/mm).

The photographic film was pressed against the exit window of the light amplifier; a special electromechanical device made it possible to displace the photographic film and change frames remotely. The function of the shutter was performed by the light amplifier: the RF-3 film was exposed when a high voltage (6 kV) of different duration was applied to the amplifier to different in-

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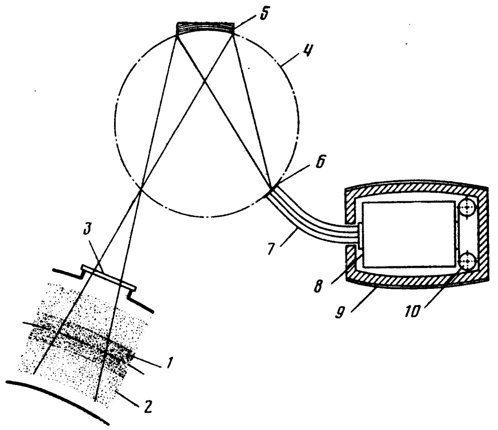

FIG. 1. Setup for the registration of the x rays: 1) hot plasma; 2) peripheral zone; 3) beryllium window; 4) Rowland circle; 5) dispersing crystal; 6) converter screen; 7) fiber optics; 8) light intensifier; 9) multilayer magnetic shield; 10) photographic film.

stants of time relative to the start of the discharge.

The light amplifier was protected against stray magnetic fields of the tokamak by a magnetic shield consisting of two layers of Permalloy and three layers of soft steel. The shield attenuated the external magnetic field by four orders of magnitude.[13]

The dispersion of the spectrograph was determined experimentally from the distance between the lines $K\alpha_1$ and $K\alpha_2$ of the characteristic radiation of chromium and manganese. The dispersion for the $\lambda = 2.1814$ Å resonance line of the He-like chromium was 1.73 mÅ/mm (Bragg angle $\theta = 67.5°$). The half-width of the instrumental contour of the light amplifier together with the converter screen, in other words the broadening of the line by the radiation detector, was 0.1 mm and thus limited the spectrograph resolution to a value $\Delta\lambda/\lambda \approx 10^{-4}$. The spectral resolution of the entire instrument, however, was somewhat worse and was estimated at $\Delta\lambda/\lambda \approx 3 \times 10^{-4}$.

Figure 1 shows the setup for the registration of the x rays.

The spectrograph was mounted on one of the inclined (30° from the horizontal plane), T-10 toroidal-chamber inlets equipped with a beryllium-foil window (100 μm).

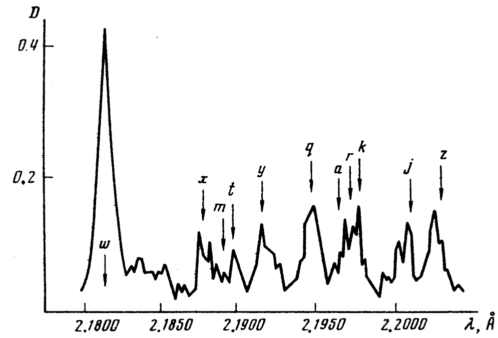

FIG. 3. Density pattern of the Cr-XXIII spectrum, obtained after nine discharges with additional electron-cyclotron heating of 500 kW power. Plasma parameters: $T_e = 2.4$ keV; $n_e = 3 \times 10^{13}$ cm^{-3}.

The x rays were registered along the central chord from the axial zone of a plasma pinch 6 cm thick.

3. EXPERIMENT AND DISCUSSION OF RESULTS

Figures 2 and 3 show the spectra of the He-like chromium, plotted at two different typical operating regimes of the tokamak—purely ohmic heating of the plasma, and with additional microwave power introduced. The line designations corresponds to those introduced in Ref. 3, and are presently standard for the indication of the dielectronic satellites and forbidden lines. The arrows correspond to the wavelengths obtained as a result of the theoretical calculation of these lines.[14] The resonance line w is assigned the calculated value $\lambda = 2.1814$ Å.

The time window, i.e., the film exposure duration, was in the first case (Fig. 2) 240 msec on the stationary part of the discharge, and in the second case (Fig. 3) 50 msec, i.e., only during the microwave pulse. The plasma parameters cited in the figure captions were obtained by other diagnostic procedures. The electron density averaged over the plasma pinch cross section was obtained by microwave sounding at a wavelength 0.87 mm.[15] The electron temperature in the region of the plasma-pinch axis was determined by the Thomson-scattering method[16] and from the slope of the continuous x-ray spectrum.[17]

Figure 4 shows one more spectrum obtained with a series of nine discharges; five of them were made with

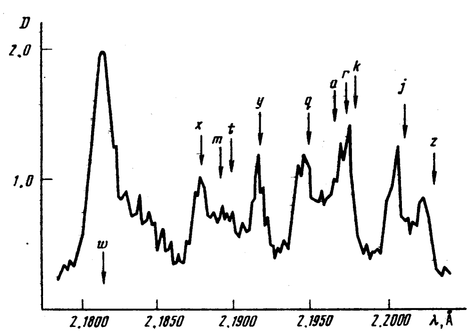

FIG. 2. Density pattern of Cr-XXIII spectrum obtained after eight discharges with ohmic heating by a current ~250 kA. Plasma parameters: $T_e = 1.5$ keV; $n_e = 2 \times 10^{13}$ cm^{-3}.

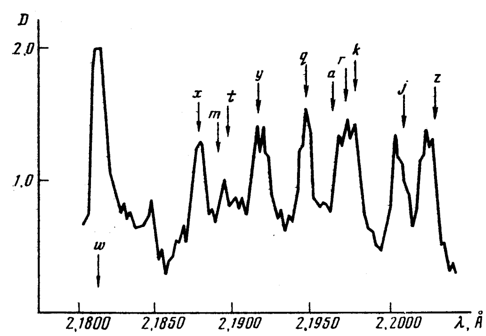

FIG. 4. Density pattern of Cr-XXIII spectrum obtained after nine discharges with different plasma-heating conditions.

TABLE I. Wavelengths in Cr-XXIII spectrum.

Symbol	Transition	λ_{theor}, Å [14]	λ_{exp}, Å
w	$1s^{2\,1}S_0-1s2p\,^1P_1$	2,1814	2.1814
x	$1s^{2\,1}S_0-1s2p\,^3P_2$	2,1879	2.1880
y	$1s^{2\,1}S_0-1s2p\,^3P_1$	2.1917	2.1918
z	$1s^{2\,1}S_0-1s2s\,^3S_1$	2.2028	2.2023
q	$1s^22s\,^2S_{1/2}-1s\,(2s2p\,^3P)\,^2P_{3/2}$	2.1948	2.1948
r	$1s^22s\,^2S_{1/2}-1s\,(2s2p\,^3P)\,^2P_{1/2}$	2.1972	2.1973
k	$1s^22p\,^2P_{1/2}-1s2p^{2\,2}D_{3/2}$	2.1978	
j	$1s^22p\,^2P_{3/2}-1s2p^{2\,2}D_{5/2}$	2.2009	2.2005

additional microwave heating of 50 msec duration. The time window was 240 msec. A comparison of all three spectra shows clearly the good reproducibility of the results.

Table I gives the experimentally determined wavelengths of the most intense well-resolved spectral lines, and the corresponding theoretical values.[1] The experimental values of the wavelengths were obtained by averaging over measurements of seven plotted spectra. As follows from Table I, the experimental data agree splendidly with the calculated predictions. The discrepancies between them do not exceed the possible experimental errors or the limits of accuracy of the theoretical calculation.

Satellites of a resonance line of a helium-like ion result from dielectronic excitation of this ion. This causes a doubly excited Li-like ion. The spectrum is the result of the transitions $1s^2nl-1s2pnl$, where $n \geq 2$. At $n=2$ the satellite lines are the most intense and differ greatly from the principal line. At $n>2$ the lines approach the resonance line and even merge with it, increasing the intensity of the resonance line. The presented density patterns shows clearly how the resonance line borders on the long-wave side with an unresolved mixture of high-order satellite lines.

With increasing electron temperature, the intensity of the satellites relative to the resonance line (e.g., the quantity I_j/I_w) decreases. In addition, in a tenuous plasma the relative intensity of the satellite lines does not depend on the density (the corona approximation). These circumstances can be used to measure the electron temperature of the plasma.[3-5]

In the present study we determined the electron temperature from the relative intensity of the j line. The necessary calculated or experimental temperature-dependence data are not available for the dielectronic spectrum of He-like chromium. Therefore the dependence of interest to us was obtained by interpolating the corresponding data known for elements (calcium, iron) that have a nuclear charge close to that of chromium.

The low accuracy of the initial data, i.e., of the values of the function $T_e=f(I_j/I_w)$, aggravated by the interpolation, makes it particularly desirable to compare the obtained data with independent temperature measurements. Table II lists the electron temperature determined by three methods: from the relative intensity of the line j, from the Thomson scattering, and from the continuous x-ray spectrum. The measurements were performed during the time that the microwave power was introduced, in an interval of 50 msec, and averaged over 3–5 discharged of the tokamak (the Thomson-scattering measurements pertain to the middle of the time interval). The figures presented point to a perfectly satisfactory agreement between all three methods of determining the electron temperature. We note, however, that the data, except for those obtained from the intensity of the dielectronic satellite, pertain to the pinch axis. No scanning over the pinch diameter was carried out in our case, so that it was impossible to determine the radial dependence of I_j/I_w. Scanning, as well as more reliable calculation data on the line intensity, will increase the accuracy of this method of determining the electron temperature.

TABLE II. Electron temperature (in 10^6 deg) determined by three methods.

Experiment	From the satellites	From the Thomson scattering*	From the continuous spectrum**
1	23	–	28
2	23	24	–

*Measurements by A. B. Berlizov.[16]
**Measurement by Yu. V. Esipchuk.[17]

Certain satellite lines can be formed also as a result of electronic excitation of an Li-like ion. The intensity of the line q, e.g., is determined almost completely by excitation of an Li-like ion. This uncovers a possibility of verifying the ionization equilibrium implied in the corona model.[3,4] The electron temperature, determined as described above from the relative intensity of the line q, was in all cases half the value obtained from the line j. This discrepancy can hardly be attributed to experimental errors. It offers evidence of violation of the ionization equilibrium: Under our conditions the plasma is less ionized than predicted by the theory.

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[1)]In addition, the long-wave lines $\lambda=2.207$, 2.210, and 2.213 Å were observed.

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