Spectrum of hydrogenlike chromium from the Frascati tokamak

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The x-ray line spectrum of hydrogenlike chromium has been observed on the Frascati tokamak (FT) by means of a high-resolution bent-crystal spectrometer. The relative positions and line intensities of the resonance Lyman-α doublet and of all the dielectronic satellite lines have been compared with the wavelengths and intensity factors calculated by several authors. The results show an overall good agreement with the theory.

In tokamaks of the present generation the observation in high resolution of x-ray line radiation emitted by highly ionized atoms has been established as a fruitful technique for plasma diagnostics.[1,2] In addition to the plasma ion temperature, deduced from the Doppler width of the main resonance line, much more information can be deduced by the analysis of the other lines present in the spectrum and arising from different excitation mechanisms—dielectronic recombination, inner-shell excitation, charge-exchange recombination, etc.—but in this case one has to rely heavily on the accuracy of calculated atomic parameters in order to deduce, for example, the electron temperature from dielectronic satellite to resonance line intensity ratios or the fractional abundances of different ionization stages.[1] In turn the validity of these calculations can be tested if parameters like the electron temperature and/or the impurity content of the plasma can be established by other diagnostic means, as it is usually the case for tokamak plasmas.

The results obtained so far refer to observations of elements up to nickel. The two-electron system is usually the most extensively observed and exploited, as the closed-shell configuration provides a high fractional abundance of the ion over a wide range of plasma conditions. On the contrary, hydrogenlike ions are more difficult to observe, but they show relatively simpler spectral features, as the only effective process in normal tokamak plasma conditions for the excitation of the satellite lines is dielectronic recombination. Therefore the satellite to resonance intensity ratio is a function of electron temperature only if a Maxwellian distribution can be assumed for the electrons, so that these lines make a good candidate to verify *ab initio* atomic data calculations.

In this Brief Report we present detailed measurements of the spectrum of hydrogenlike chromium observed in high resolution on the Frascati tokamak (FT). As an example of the results obtained we show in Fig. 1 the spectrum recorded over a series of discharges with similar conditions: toroidal magnetic field 8 T, plasma current 300–350 kA, electron temperature 3 keV$\pm$10%, and electron density ranging from 3×10^{13} to 7×10^{13} cm^{-3}.

The chromium ions are naturally present in the hydrogen or deuterium plasma as trace impurity eroded from the Inkonel limiter and the stainless-steel walls of the vacuum vessel; their concentration is estimated to be normally of the order of $\sim10^{-4}$ that of the electrons.

The spectrum was recorded by means of a high-resolution bent-crystal spectrometer of the Johann type[3] mounting a quartz crystal cut parallel to the (213) plane and having 4 m of curvature radius. The detector was a position-sensitive multiwire proportional chamber with 0.3 mm of space resolution and a delay-line read-out system. A 4202 LeCroy TDC (time to digital converter) feeding a 3588 histogramming memory allowed the acquisition of up to 32 spectra of 512 channels each during a single FT pulse, with a time resolution of 35 msec. Each channel corresponds to 6.8×10^{-5} Å, the instrument resolution being 10^{-4} Å.

Due to the narrow access to the plasma in our machine, the observable spectral range for a given setting of the instrument is only $\sim13\times10^{-3}$ Å. The full spectrum was therefore taken for four different crystal and detector positions. In each section one clearly recognizable line was present also on the previous section, thus allowing a good wavelength and intensity normalization.

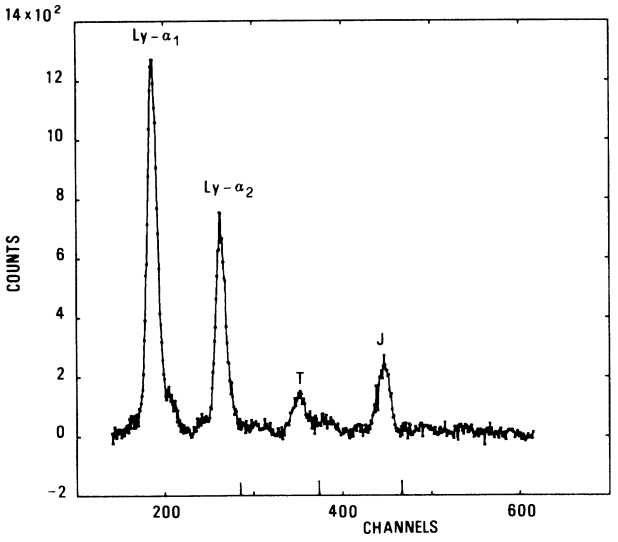

FIG. 1. Experimental spectrum of hydrogenlike Cr. The vertical bars show where the different sections of the spectrum have been joined together. A constant background level has been subtracted from each section separately.

The estimated contribution due to this procedure to the relative error on the wavelength of the farthest line in the full spectrum is not greater than 4×10^{-4} Å. Several pulses for each position were accumulated for better statistics. A constant continuum background level has been subtracted from each section separately. The spectrometer was not calibrated in wavelength, and both the instrument spectral dispersion and absolute wavelength scale are determined by making use of the theoretical values of the Lyman-α doublet lines. The complete experimental spectrum is shown in Fig. 1. The vertical slashes indicate where the different sections of the spectrum have been joined. The lines marked as T and J are a blend of several transitions.

We have compared our experimental results with the data for the dielectronic recombination satellites intensities and wavelengths published by Karim and Bhalla in Ref. 4, those by Vainshtein and Safronova in Ref. 5 where only $n=2$ satellite are listed, and with the calculations by Dubau, Loulergue, and Cornille;[6] for the relative intensities of the Ly-α doublet we refer to the works by Ljepojevic *et al.*,[7] Parpia and Johnson,[8] and Mewe *et al.*[9]

The first problem we deal with is the intensity ratio between the two components of the Lyman doublet. They should be in the ratio of their statistical weights, that is 2:1, but the magnetic dipole transition $M1$ $2s\ ^1S_{1/2}\rightarrow 1s\ ^1S_{1/2}$, whose transition rate scales as Z^6, makes a measurable contribution to the intensity of the Ly-α_2 line, from which it cannot be resolved. In Ref. 7 the effects due to proton collisions, totally negligible for the densities we operate at, are also discussed, together with those due to high-n unresolved satellites. We used the parametric formula by Mewe for the electric dipole transition $E1$ and $M1$ excitation rates and the branching ratio between the two-photon decay $2E1$ and the $M1$ decay from Parpia and Johnson to estimate the correction factor needed to take into account the $M1$ transition. To estimate the effect of the satellites with $n\geq 3$, we added the intensity factors explicitly calculated for all the transitions with $n=3,4,5$ falling beneath the lower and upper component of the doublet, according to Ref. 6, and by following the procedure described by Dubau[10] we estimated the contribution from $n\geq 6$ to infinity. The result of this calculation is shown in Fig. 2, where the ratio $I(\text{Ly-}\alpha_2)/I(\text{Ly-}\alpha_1)$ is plotted against temperature between 1 and 10 keV. The value deduced from Ref. 7 agrees with these results. As expected the temperature dependence of the $M1$ line is very weak, while the effects of the unresolved satellites are almost negligible above 5 keV. The

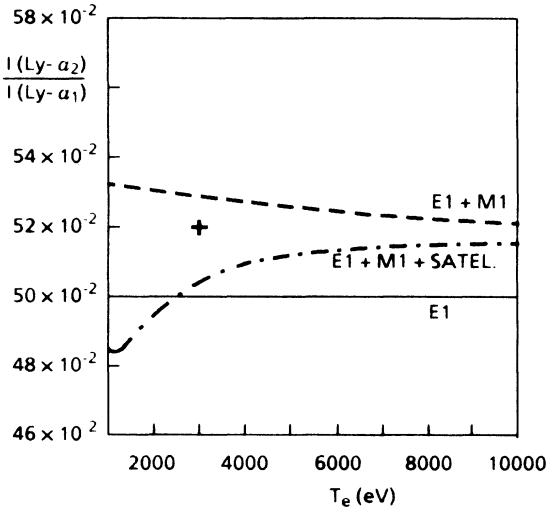

FIG. 2. Lyman doublet lines intensity ratio, electric dipole transitions only (——), including the $M1$ component (— — —) and taking into account the contribution of unresolved satellites (—·—·—). The symbol shows the estimated ratio from Ref. 7.

TABLE I. List of wavelengths for the resonance transitions and the $n=2$ dielectronic satellite lines.

	Transition	λ^a (Å)	λ^b (Å)	λ^c (Å)
Ly-α_1	$1s\ ^2S_{1/2}\rightarrow 2p\ ^2P_{3/2}$	2.0901	2.0894	2.0901
Ly-α_2	$1s\ ^2S_{1/2}\rightarrow 2p\ ^2P_{1/2}$	2.0955	2.0947	2.0955
	$2s2p\ ^1P_1\rightarrow 1s2s\ ^3S_1$	2.0899	2.0905	2.0901
	$2p^2\ ^1S_0\rightarrow 1s2p\ ^1P_1$	2.0952	2.0952	2.0951
	$2s2p\ ^1P_1\rightarrow 1s2s\ ^1S_0$	2.0997	2.1007	2.0999
T	$2p^2\ ^1D_2\rightarrow 1s2p\ ^3P_2$	2.1007	2.1010	2.1008
	$2s2p\ ^3P_2\rightarrow 1s2s\ ^3S_1$	2.1021	2.1022	2.1021
	$2p^2\ ^3P_2\rightarrow 1s2p\ ^3P_1$	2.1027	2.1031	2.1025
	$2s2p\ ^3P_1\rightarrow 1s2s\ ^3S_1$	2.1058	2.1061	2.1060
	$2p^2\ ^3P_2\rightarrow 1s2p\ ^3P_2$	2.1063	2.1066	2.1066
J	$2p^2\ ^1D_2\rightarrow 1s2p\ ^1P_1$	2.1070	2.1070	2.1072
	$2p^2\ ^3P_0\rightarrow 1s2p\ ^3P_1$	2.1070	2.1074	2.1070
	$2s2p\ ^3P_0\rightarrow 1s2s\ ^3S_1$	2.1071	2.1074	2.1074
	$2p^2\ ^3P_2\rightarrow 1s2p\ ^1P_1$	2.1126	2.1127	2.1130
	$2s^2\ ^1S_0\rightarrow 1s2p\ ^3P_1$	2.1190	2.1190	2.1186
	$2s^2\ ^1S_0\rightarrow 1s2p\ ^1P_1$	2.1291	2.1288	2.1292

[a]From Ref. 4.
[b]From Ref. 5.
[c]From Ref. 6.

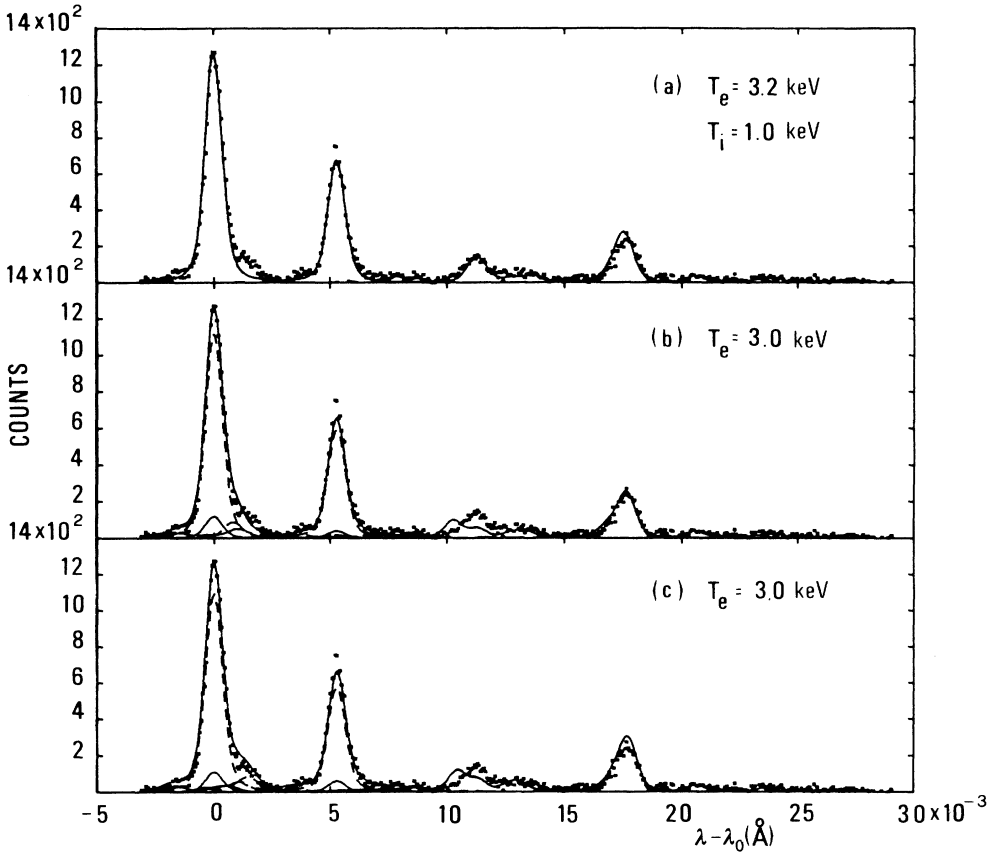

FIG. 3. The experimental spectrum compared with theoretical predictions. (a) Wavelengths and intensity factors from Vainshtein and Safronova (only the $n=2$ transitions are present); (b) data from Karim and Bhalla and (c) from Dubau. The wavelength scale is determined from the theoretical position of the Ly doublet for each data set.

experimental value measured from the spectrum of Fig. 1 is 0.56±0.07, to be compared with a calculated value of 0.505 at our temperature.

In order to compare the experimental wavelengths with the theoretical calculations we derive for each data set a wavelength scale from the theoretical position of the resonance doublet, see Table I. We note that Karim and Bhalla produce for the doublet the values 2.0901 and 2.0955 Å, in very good agreement with the values found by Mohr,[11] whereas Vainshtein and Safronova give 2.0894 and 2.0947 Å. In comparison with the experimental data we adopt the procedure of applying a suitable solid shift to the calculated satellite wavelengths, as first suggested in Ref. 12, to make them match the experimental results. The only set of data for which this procedure was not necessary is the one by Vainshtein and Safronova: all the $n=2$ dielectronic satellites are found in close agreement with the experiment. For Karim and Bhalla the applied shift was -8×10^{-4} Å for the set of wavelengths obtained by Hartree-Fock-Slater calculations. In the case of the Dubau data, an overall good agreement is found if a shift of -7×10^{-4} Å is applied. We note that this shift nearly compensates for the difference in the theoretical position of the resonance doublet with respect to the Vainshtein and Safronova values. For both these authors the only remarkable discrepancy is relative to the position of the T satellite. In Figs. 3(a)–3(c) the experimental data are shown with the simulated spectra calculated using the three sets of theoretical data.

All three authors give values of the satellite intensity

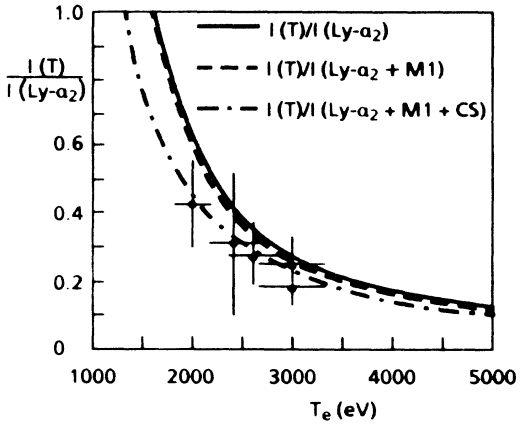

FIG. 4. Dielectronic satellite line T to Ly-α_2 intensity ratio as a function of electron temperature (——); including the $M1$ contribution (— — —) and the unresolved satellites (—·—·-).

factors,

$$F_2(s)=(g_s A_r^{sf} A_a^{si}) \Big/ \left[\sum_{f'} A_r^{sf'} \sum_{i'} A_a^{si'} \right]$$

that are within few percent from one another, at least for the most intense lines, and the experimental spectrum can be well reproduced by the theoretical one assuming an electron temperature of ~ 3 keV with all three sets of data. It is especially worth noting that the intensity of both clusters of lines T and J can be well described by the same temperature, any discrepancy appearing more due to the positions of the single lines rather than to their intensity factors.

A more detailed analysis of the dielectronic satellite to the resonance intensity ratio has been performed on a different series of discharges with varying plasma parameters and with the instrument set as to record the Ly-α_2 and the T lines. The electron temperature was measured by the electron cyclotron emission diagnostic and checked to be in agreement with the Thomson scattering determinations. In Fig. 4 the measured ratios with their experimental errors are plotted against T_e. The dotted and solid lines represent the theoretical curves, respectively, with and without the contribution to the Ly-α_2 due to the $M1$ transition and the close satellites. A good agreement is found between theory and experiment, thus confirming the accuracy of the calculated intensity factors.

In conclusion, we have compared the measured spectrum of hydrogenlike chromium with theoretical calculations of wavelengths and intensity factors. We have found that the values given by Vainshtein and Safronova are able to reproduce accurately the position of all the line in the spectrum, whereas the other authors, although able to describe in detail most of the $n=2$ and $n=3$ satellites, have a discrepancy for the position of the line labeled T. The value of the line intensities is accurately reproduced by all the considered calculations. We have measured the intensity ratio of the T line to the Ly-α_2 line as a function of temperature. The experimental data fit the calculations very well, provided the contribution of unresolved dielectronic satellites is included in the Ly-α_2 intensity. The intensity ratio of the two components of the Lyman doublet has also been measured and its value, although systematically higher, fits within the error bar the theoretical value, obtained taking into account the magnetic dipole transition of the $2s$ state.

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