RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 39, NUMBER 7 APRIL 1, 1989

Highly ionized uranium emission in the soft-x-ray region 50–100 Å

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(Received 27 December 1988)

Time-resolved uranium spectra emitted from a relatively low-density ($n_e \sim 10^{13}$ cm^{-3}), high-temperature ($T_e \sim 1$ keV) plasma confined in the Texas experimental tokamak (TEXT) have been recorded in the 50–100 Å range. It is found that narrow emission bands originating from transitions within charge states having $5p^6 5d^k$ and $5s^2 5p^k$ ground configurations, U XV to U XXXI, dominate these spectra. The identification of the transition arrays is based on the comparison with both *ab initio* intermediate-coupling relativistic level structure computations including configuration-interaction effects for the simple cases and, for complex charge states, with the predictions of the unresolved transition array model.

Spectra emitted by highly ionized heavy atoms are of great interest because of their application to soft-x-ray laser and inertial confinement research.[1,2] From a theoretical point of view, these spectra are of interest for the testing of relativistic structure calculations[3] and novel approaches to the treatment of unresolved transition arrays (UTA's).[4]

We have shown in previous works that the soft x-ray emissions from high-Z elements (Z=58–82), emitted over a very wide range of electron temperatures and densities by a variety of different sources, such as vacuum sparks, tokamak, and laser-produced plasmas, are characterized by quasicontinuous bands.[5–8] These bands originate from the superposition of lines emitted from the n=4 shell (4-4) transitions by many charge states with $4s^2 4p^k$ and $4p^6 4d^k$ ground configurations. In the present work we have extended the previous research to uranium (Z=92) by analyzing transitions within the n=5 shell. Although the experimental spectra were expected to be very complex, the analysis was facilitated by the specific properties of the emitting tokamak plasma. Indeed, the slow diffusion of the charge states across the long-lived (~400 msec), extended plasma (r=27 cm) makes it possible to follow the relative time histories of the emitted spectral features, thus allowing discrimination between the emitting charge states. Second, the relatively low electron density ($n_e \sim 10^{13}$ cm^{-3}) of the tokamak plasma makes the emission from doubly excited states much less important than in laser-produced plasmas.

To the best of our knowledge, highly ionized uranium spectra in the range under discussion have been previously reported by Carroll *et al.*[9] and Hodge *et al.*[10] In the first work, only relatively low charge states have been observed: U XIII and U XV lines and a broad array centered above 90 Å were obtained in low-energy laser-produced plasmas. In the experiments performed recently by Hodge *et al.*, time-integrated spectra were recorded in the 20–120 Å range from the irradiation of uranium targets with an intermediate energy laser beam (several joules). However, due to the superposition of large numbers of lines emitted by many charge states, this entire domain presents a continuous and rather amorphous structure in which it is difficult to identify individual transitions. Seely *et al.* have observed Co I-, Cu I-, and Zn I-like uranium lines at shorter wavelengths in spectra generated by the OMEGA high-energy laser.[3] In the present experiment, we have injected uranium into the Texas experimental tokamak (TEXT) plasma using the laser blow-off method.[11] The target plasma parameters were similar to those described in our previous reports (e.g., Ref. 8). However, in order to obtain higher charge states, deuterium and helium discharges have been used in addition to those in hydrogen. (For a given set of values of the electron density, plasma current, and confining toroidal field, the central electron temperatures which can be obtained increase with the mass of the gas used in the discharge.) Unlike the earlier high-Z injection experiments, the very strong radiative cooling due to the uranium emission severely perturbed the plasma by lowering its temperature in most of the injection discharges. By defocusing the laser beam on the uranium slides, we could obtain small, unperturbing injections but they produced weak and noisy spectra. As a result, only "intermediate" charge states U XV to U XXXI have been clearly identified in the tokamak spectra. Figure 1 shows the two situations: In the upper part of the figure the changes in both central electron density and integrated soft x-ray emission are small, indicating a small perturbation of the central electron temperature (the soft-x-ray signal is characteristic of highly ionized intrinsic impurity emission). The lower figure shows a very significant drop in the soft x-ray emission, thus indicating strong radiative cooling of the plasma.

The uranium spectra have been obtained using a time-resolving, multispectral instrument photometrically cali-

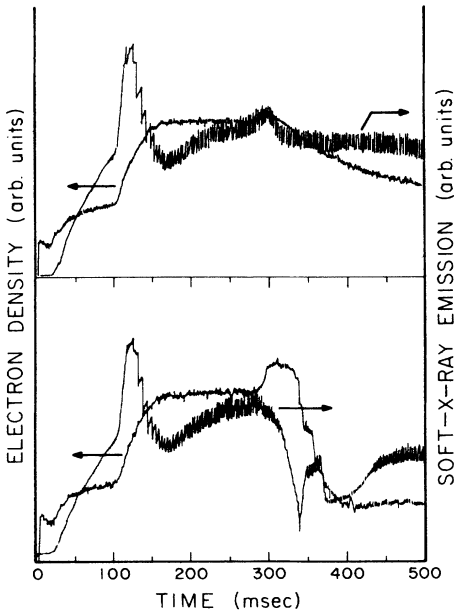

FIG. 1. Traces showing the average electron density and soft-x-ray emission from the TEXT plasma during uranium injection experiments; the upper figure represents a relatively unperturbed injection while in the lower trace, the strong increase in the density and decrease in the soft-x-ray signal indicate large amounts of uranium cooling the plasma.

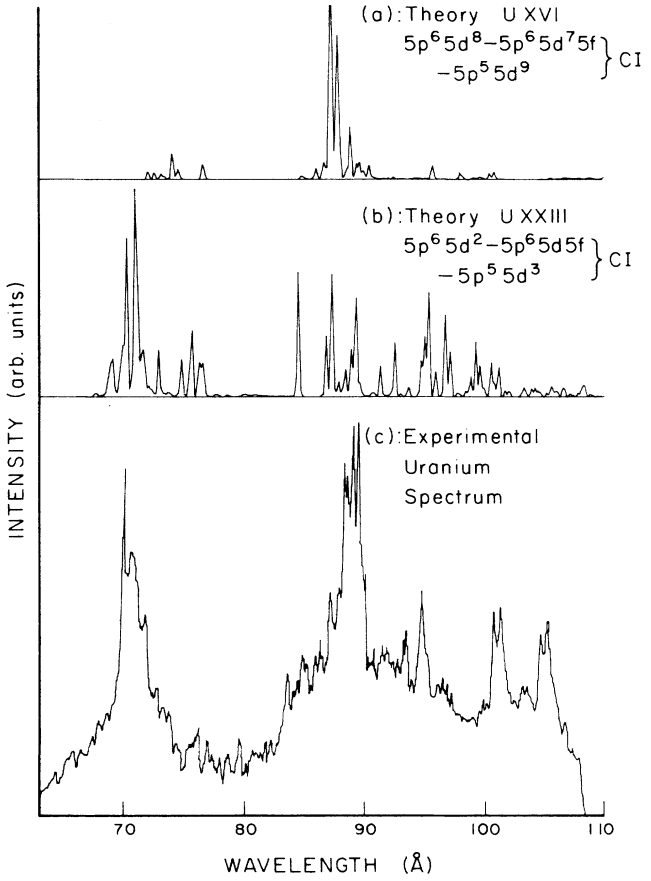

FIG. 2. Comparison between theory and experiment: The two upper traces represent theoretical computations of the $5p$-$5d$ and $5d$-$5f$ transitions with configuration interaction (CI) between the two excited states for two charge states. The lower trace is an experimental uranium spectrum integrated over 13.2 msec.

brated at the SURF II synchrotron facility,[12] which allowed recording the entire range of interest in a single discharge, with a time resolution of 13.2 msec. The wavelength calibration is obtained by a polynomial fit to known intrinsic impurity lines present in the spectra previous to the uranium injection. Several frames after injection can be added to improve the signal to noise. Also the frame previous to the injection is subtracted from the frames recorded after the injection, thus giving a clean uranium spectrum. A 10-μm entrance slit was used in order to enhance the spectral resolution (0.7 Å).

The spectrum obtained between 60 and 110 Å from a perturbed, deuterium target plasma is shown in Fig. 2. As one can see the spectrum is dominated by two broad structures, centered and peaked at 70 Å and slightly less than 90 Å. Individual lines and blends of lines appear on the broad-band structure. (The present Communication analyzes only the unresolved features; the line spectrum in this range and above 100 Å will be the subject of a subsequent paper.) The identification of the transitions responsible for the theoretical spectra is based upon *ab initio* energy-level structure calculations. The charge states considered were all those having $5l^k$ ground configurations, from $4f^{14}5s$ (U XXXII) to $4f^{14}5s^25p^65d^{10}$ (U XV). Two types of calculation have been performed; for ions having relatively simple ground-state configurations, such as $5s$, $5s^2$, $5p$, $5p^6$, $5d$, $5d^2$, and $5d^8$, *ab initio* relativistic calculations of the ground and excited $5l5l'$ configurations have been performed. In the case of ions with the open $5p^65d^k$ shells, the mixing between the excited $5p^55d^{k+1}$ and $5d^{k-1}5f$ configurations has been considered. For more complex ground-state ions, with many d electrons in the ground state such as $5p^6d^5$, the UTA formalism[4] has been used to compute the mean wavelength and the spectral width of the arrays originating within the d-f transitions. The treatment of p-d transitions by the UTA formalism would be irrelevant; this formalism calculates one mean wavelength and variance for the entire array whereas the p-d transitions are split into two subarrays corresponding to transitions from $5p^5_{1/2}5d^{k+1}$ and $5p^5_{3/2}d^{k+1}$, respectively. The mean wavelength of the transitions from the subarrays have been calculated using statistically weighted mean energies of the corresponding array levels (not line strength weighted as in the UTA formalism). This may explain partly, the discrepancies between the observed and the calculated mean wavelengths.

Table I summarizes the results of these computations for U XVI to U XXIII. The theoretical traces in Figs. 2(a) and 2(b), clearly show the effect of configuration interaction on the $5p$-$5d$ transitions: The $5p^65d^k$-$5p^5_{1/2}d^{k+1}$ subarray, at the shorter wavelength ($\sim$70 Å) is strongly enhanced comparatively with the second subarray around

TABLE I. Theoretical mean wavelength computations for the $5d$-$5f$ and $5p$-$5d$ arrays in U XVI to U XXII. Wavelengths are measured in angstroms.

Ion	k	$\bar{\lambda}(5p^6 5d^k - 5p^6 5d^{k-1} 5f)$	$\bar{\lambda}(5p^6 5d^k - 5p^5 5d^{k+1})$ $J=\frac{1}{2}$	$J=\frac{3}{2}$
U XVI	9	89.53	74.75	113.24
U XVII	8	89.50	74.35	113.2
U XVIII	7	89.57	73.90	113.15
U XIX	6	89.93	73.52	113.18
U XX	5	90.39	73.20	113.29
U XXI	4	91.0	72.76	113.33
U XXII	3	91.77	72.42	113.48
U XXIII	2	92.66	72.0	113.671

113 Å. This prediction is confirmed in the lower trace (C), presenting the experimental spectrum: the two dominant structures are centered at 70 and 88 Å, corresponding to the low-wavelength subarray and the $5d$-$5f$ transitions.

Higher-charge states, i.e., those having $5s^2 5p^k$ ($k=1$-6) ground-state configurations U XXV-U XXX, have ionization potentials roughly between 700 and 900 eV. *Ab initio* computations show that the lines originating from $5s^2 5p^k$ to $5s^2 5p^{k-1} 5d$, $5s 5p^{k+1}$, and $5s^2 5p^{k-1} 6s$ transitions would also concentrate around 70 and 90 Å; thus they cannot be distinguished from the emission of U XVI to U XXV discussed above. An indication of their presence in the spectrum is given by the time-resolved spectra. Figure 3 presents the uranium spectrum between 70 and 110 Å during the first frame after injection, 26 msec later, and 65 msec later in the discharge. (The absolute brightness of the middle spectrum is much higher than the other two.) The spectra are recorded in a strongly perturbing uranium injection, illustrated by the lower current and density traces in Fig. 1. The relative intensity ratio of the two bands at 70 and 90 Å is illustrative of the change in the relative abundances of ions having $5p^6 5d^k$ and $5s^2 5p^k$ ground states. Before the perturbation and the collapse of the central electron temperature (about 35–40 msec after the uranium injection) the peak of the band at 88 Å is higher than that at 70 Å. The increasing amount of higher-charge states in time is reflected by the enhancement of the 70-Å band over that at 88 Å (intermediate frame t_0+26 msec). This is due to the fact that both the relative weight of the $5p$-$5d$ transitions originating from charge states with fewer d electrons in the ground state (i.e., higher-charge states) increases (see discussions in Ref. 13 for the similar situation in the $n=4$ shell) and more ions with $5s^2 5p^k$ ground configuration are emitting. At a later time ($t+65$ msec), the plasma is strongly cooled and again relatively lower ionization states dominate the spectrum as in the beginning.

In conclusion, time-resolved soft-x-ray emission of highly ionized uranium has been obtained from the TEXT plasma. The experimental spectra show the existence of two well-separated spectral features centered at 70 and 88 Å, and lines originating from ions with simple ground states such as $5s^2 5p^6$, $5p^6 5d$, and $5p^6 5d^{10}$, superimposed on them. The relatively low density of the tokamak plasma ensures that mainly transitions between low-lying excited states and the ground are responsible for the emission. The comparison of the time-resolved experimental spectra with *ab initio* energy-level structure computations lead to the identification of the band emissions as originating mainly from $5p^6 5d^k$-$5p^5 5d^{k+1}$, $5d^k$-$5d^{k-1} 5f$, $5s^2 5p^k$-$5s 5p^{k+1}$, and $5s^2 5p^k$-$5s^2 5p^{k-1} 5d$ transitions in the ions U XVI to U XXXI. A further, more extended work will present detailed theoretical computations and an attempt to identify individual transitions of U XXV, U XXXI, and U XXXII.

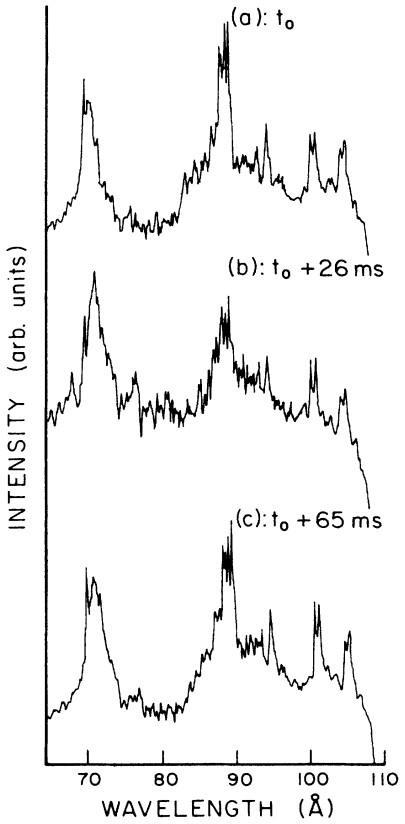

FIG. 3. Time history of the spectrum in the 70–110 Å range.

The authors would like to acknowledge discussions with Dr. William L. Hodge on the laser-produced uranium plasma and theoretical computations other than ours. The research was supported by the U.S. Department of Energy Grants No. DE-FG02-85ER53214 at the Johns Hopkins University and No. DE-FG05-88ER53267 at the University of Texas.

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