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Plasma spectroscopy of $n=4$ to 3 C IV and N V lines in hot and dense plasmas

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The spectral line profiles of $n=4$ to 3 transitions emitted by the Li-like ions of carbon and nitrogen in a hot, dense hydrogen plasma are calculated and compared to measurements. The excellent agreement with the independently measured temperature and density establishes the theoretical model and validates its use as a plasma diagnostic. The effect of spectral resolution on the accuracy of the determination of the plasma conditions is examined.

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The profiles of lithiumlike transitions of ionized emitters arising in hot dense plasmas are of interest in a number of fields, including extreme ultraviolet laser development [1], the study of radiation transport in stellar atmospheres [2], and for the analysis of the conditions in experiments on inertial confinement plasmas [3]. On the one hand, the measurement of line profiles from these transitions at high resolution and stable plasma conditions presents a difficult experimental problem [4]. On the other hand, the theoretical analysis is also complex due to the simultaneous importance of both collisional and ion Stark broadening effects and also because of the large number of sublevels that are involved in the transitions.

We present here the interpretation of experimental measurements of the spectra of C IV and N V vacuum ultraviolet (vuv) $n=4$ to 3 transitions. The analysis of these data is further complicated by the existence of a relatively large apparatus function and the presence in various orders of lines arising from other ion stages. Nevertheless, it will be shown that it is possible to extract the diagnostic information contained in the underlying line shape of the radiation emitted with an accurate computation of the spectral profile convolved with the apparatus function. This is accomplished by using a fast computer code developed for this purpose that calculates the line shapes of complex ions in hot and dense plasmas [5].

The measurements of the spectral profiles were carried out using a gas-liner pinch device that resembles a large aspect ratio z-pinch discharge as described previously [6]. Hydrogen, used as a driver gas, is preionized and after compression forms a hot and dense central plasma column. Varying amounts of a test gas, the atomic species of interest, become concentrated in the central region of homogeneous plasma conditions when injected along the axis of the pinch. The homogeneity has been verified in Ref. [7]. Furthermore, by comparing the calculated and measured intensity ratios of the $3p\,^2P^O_{3/2}-3s\,^2S_{1/2}$ to the $3p\,^2P^O_{1/2}-3s\,^2S_{1/2}$ and of the $2p\,P^O_{3/2}-2s\,^2S_{1/2}$ to the $2p\,^2P^O_{1/2}-2s\,^2S_{1/2}$ multiplet lines of C IV and N V, radiation transport (self-absorption) has been shown to be negligible for the investigated transitions with these plasma conditions. The intensity ratios of 2:1 are obtained to within 5%, in good agreement with the values calculated with LS coupling, and, thus, verify that the $4f-3d$ spectral lines of C IV and N V are indeed optically thin. The plasma temperature and density are determined by Thompson scattering [8]. Plasma parameters obtained by this procedure are accurate to within 10–20 %. The plasma is observed side on through a port in the midplane of the discharge with a 1-m spectrometer for the vacuum-ultraviolet spectral range, McPherson model 225 with a 1200 lines/mm grating blazed at 120 nm. The width of the entrance slit is 25 μm and the height is 2 mm. The spectrometer is equipped with a microchannelplate (MCP) of the chevron type, a Galileo model CEMA 3025, in the exit plane that is gated with a pulse duration of 20 ns. The P20 phosphor at the exit side of the MCP is imaged on a detector head of an optical multichannel analyzer system. The reciprocal linear dispersion is 0.2 Å/pixel. The apparatus profile is obtained with a narrow N I impurity line emitted from an argon miniarc; it is well approximated by a Lorentzian with 1.8 Å full width at half maximum (FWHM) in first order. As will be seen, this function is large compared to the plasma broadening. We note that the Doppler broadening was negligible for all spectra analyzed.

The line profile calculations performed here for the $n=4$ to 3 C IV and N V transitions are based on the usual separation of the effects of the fast electron impact collisions and the quasistatic Stark effect of the slowly moving ions in the plasma. In this approximation the Stark

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effect due to the ion microfield at the radiator splits each radiative transition into a number of components. The electron collisions then produce a homogeneous broadening of each Stark component of the radiative transition. Assuming that the ions are static during the radiation process, an average over the ion microfield perturbation at the radiator is performed. This results in the static or inhomogeneous broadening contribution to the line shape. The profile produced by this method is composed of a sum of averaged components for each of the radiative transitions. The components are characterized by a central frequency, a homogeneous width, and a complex amplitude. In this static microfield case, each radiative transition can be interpreted as the weighted sum of a number of separate radiative channels.

The transitions of C IV and N V, which are to be examined, all arise from levels that have the doublet structure typical of the $\Delta n = 1$ transitions of Li-like ions. In the absence of the Stark effect, each transition would have the three radiative constituents corresponding to the $|\Delta J| = 0, 1$ fine structure components. However, since plasma fields separate these three radiative transitions into a large number of channels, corresponding to the splitting of the m_j sublevels, the analysis of the transition profile requires much more than the three original components. Only through a calculation capable of including this large number of channels can a line shape for comparison with the experiment be produced. As will be seen, this profile computation is critical for diagnostic purposes when, as in the following, a convolution with a large apparatus function must be performed to compare the theoretical and the observed profile.

In Fig. 1, the computed profile of the $4d$-$3p$ transition of C IV is convolved with the instrument function and compared to the experimental data taken in first order. This convolution of the calculated profile with the instrument function produces a profile in which much of the detail seen in the calculated line shape is smoothed out. The large asymmetry on the short wavelength side of the spectral profile is the forbidden $4f$-$3p$ line. The same transition in N V with identical plasma parameters is presented in Fig. 2. Again the agreement between the theoretical profile and the experimental points is quite good. The theoretical profile including the apparatus response provides a positive identification of the observed spectral line shape and is useful for the diagnostic of the plasma conditions.

The next transition to be examined, the C IV $4f$-$3d$ transition, has been measured in second order, and the improved resolution now reveals important spectral features that must be identified in order to understand the data. An additional complication is the appearance of several C III lines in the wing of this profile. Their presence could, without a good line shape model, compromise the interpretation. The complicated situation can be seen in Fig. 3, where the theory convolved with the apparatus function is compared to the experimental data. For this transition the calculation showed that the forbidden $4d$-$3d$ component is again merged with the allowed C IV $4f$-$3d$ line. For this reason, the large asymmetry seen in the data on the long wavelength wing is not due to the forbidden transition. A good fit with the experiment is obtained if this asymmetry is considered to be caused by another transition not belonging to the set associated with the calculated profile. This feature, identified as the C III $2p3s$-$2p^2$ transition at 585 Å in second order and observed in first order in Ref. [9], as well as the large C III $2p^2$-$2p2s$ transition at 1175 Å, have been fitted to Lorentzian shaped resonances and added to the computed C IV line profile. The experimental data then closely fit the theoretical calculation for the measured plasma density and temperature. It is important to understand

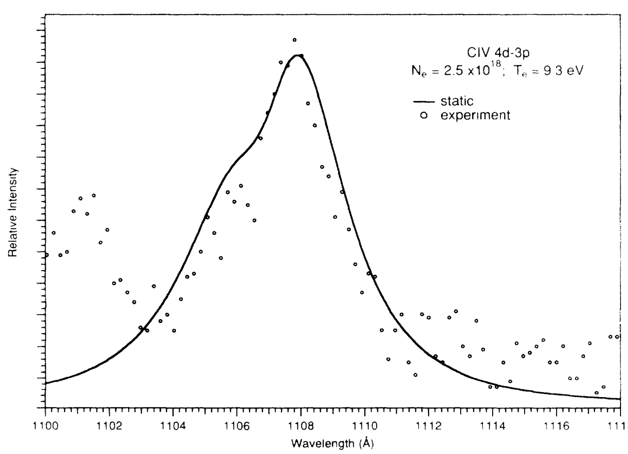

FIG. 1. Comparison with experiment of the theoretical profile of the lithiumlike, C IV dipole allowed, $4d$-$3p$ transition at 1108 Å. The line profiles are presented as relative intensity vs wavelength in angstroms. The electron temperature and density are $T_e = 9.3 \pm 1.9$ eV and $N_e = (2.5 \pm 0.5) \times 10^{18}$ cm^{-3}. Error bars are rms values from ten measurements. The theoretical profile is calculated for these plasma parameters and include the 1.8-Å FWHM apparatus function. The experimental points are indicated by circles; the solid curve is the theory.

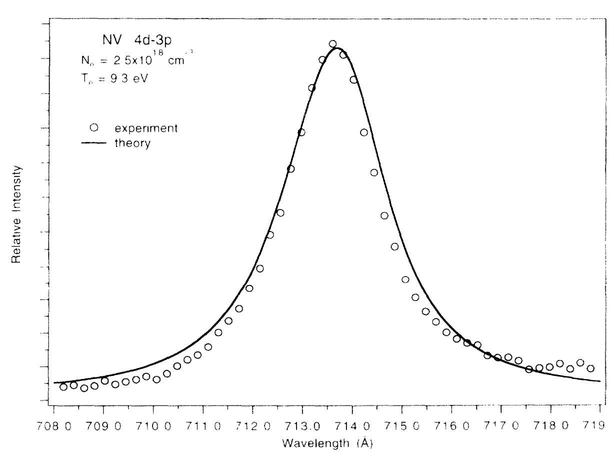

FIG. 2. Comparison of the theoretical N V $4f$-$3p$ profiles to the experiment. The conditions are the same as Fig. 1, and the transition includes the 1.8-Å FWHM apparatus function. The experimental points are indicated by circles; the solid curve is the theory.

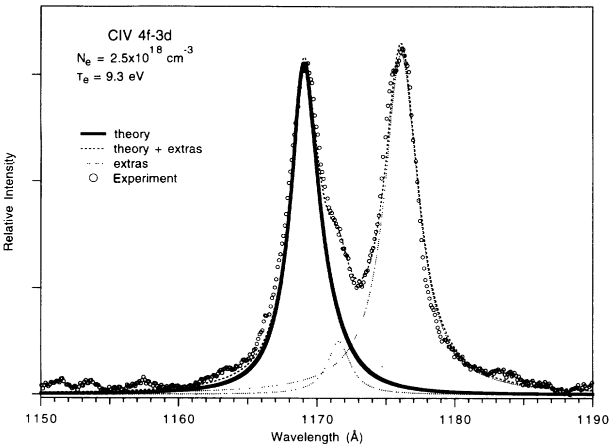

FIG. 3. Comparison of the theoretical O IV $4f$-$3d$ profile to the experiment. The plasma conditions are the same as in the previous figures, but the transition has been measured in second order and has a 0.9-Å FWHM apparatus function, half that of Figs. 1 and 2, which were measured in first order. The experimental points are indicated by circles and the calculation is labeled as in the previous figures. Also included is the contribution of the 585-Å C III $2p3s$-$2p^2$ transition in second order, as well as the large C III $2p^2$-$2p2s$ transition at 1175 Å, approximated by Lorentzians and described by dotted lines. The total of the theory and these two transitions is indicated by the dashed line.

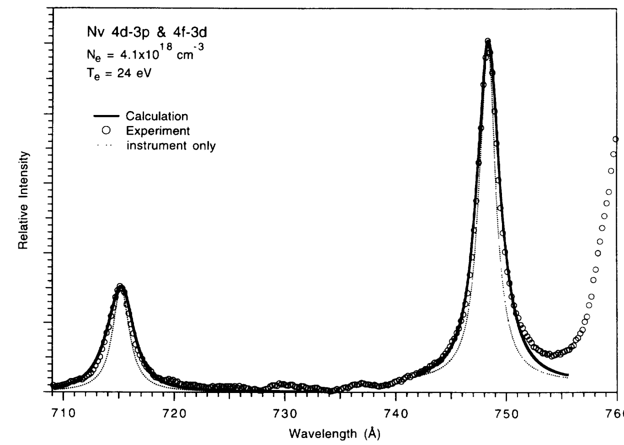

FIG. 4. The N V spectrum between 710 and 760 Å with the profiles of the N V $4d$-$3p$ and $4f$-$3d$ transitions measured in first order and compared to the apparatus width and to the theoretical line convolved with the 1.8-Å FWHM apparatus function. The experimental points are indicated by circles and the apparatus function alone is described by a dotted line. The calculation, convolved with the apparatus function, is labeled by the solid line. The temperature T_e is 24±4.8 eV and the electron density N_e is 4.1±0.82 10^{18} cm^{-3}.

that the only free parameters used in this calculation are the plasma conditions and the widths of the two Lorentzian lines in the wing. The good agreement of the *C* IV $4f$-$3d$ line shape with the data after addition of the two extra features is an indication of the usefulness of these calculations both for diagnostics and for spectral identifications.

The N V $4d$-$3p$ and $4f$-$3d$ transitions measured in first order in the 710–760 Å spectral region have been calculated, convolved with the apparatus function, and compared to the experimental data in Fig. 4. The comparison of the $4d$-$3p$ profile with the data has already been studied in Fig. 2. We observe again that the fit of the calculation with the data in Fig. 4 is good.

To illustrate the importance of spectral resolution, data from the same transition, taken in both first order and fourth order, are compared in Fig. 5 to each theoretical profile convolved with the corresponding apparatus function. The fourth order data displayed in this figure contain a small contribution from the N V $8f$-$5g$ transition in second order on the short wavelength wing, which, of course, is not present in the first order data. It is for this reason that the first order profile and the red wing of the fourth order data almost exactly match the theory, while the fourth order blue wing is not well fitted by the calculation. The profile measured in fourth order has an apparatus width of the same order as the Stark width. Since this ratio is one-fourth that of the first order measurement, the fourth order data permit diagnostics with a much higher confidence level. The excellent agreement of the data and the calculation with both sets of measurements in Fig. 5 illustrates that information on the plasma

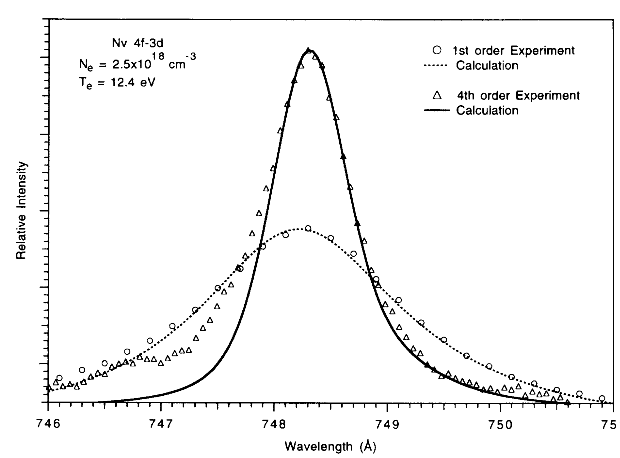

FIG. 5. The comparison of the calculated shape of the N V $4f-3d$ transition at 748.2 Å with two sets of experimental data with different spectral resolution. The experimental points are indicated by circles for the first order and triangles for the fourth order. The calculation is labeled by a dotted line in first order and a solid line in fourth order. The theory is convolved with an apparatus FWHM of 1.8 Å for comparison with the first order measurement and an apparatus FWHM of 0.45 Å for the fourth order measurement. The N V $8f-5g$ transition in second order appears on the short wavelength wing of the fourth order data and, excluding this feature, there is good agreement for both sets of data simultaneously. The temperature T_e is 12.4±2.5 eV and the electron density N_e is 2.5±0.5×10^{18} cm^{-3}.

parameters can be obtained through the comparison of the theoretical profile with data taken with a resolution that would normally nor permit diagnostics.

The profiles of a group of Li-like vuv transitions in carbon and nitrogen have been calculated and compared to the corresponding set of experimental data. The computed and measured profiles are in excellent agreement and are consistent with the plasma electron temperature and density determined in independent experiments. Their comparison was undertaken to validate these computations for the diagnosis of plasmas where, as is the usual case, independent measurements of the plasma conditions are not available. It is of importance to note that in spite of an instrumental profile in these experiments with a width larger than the Stark broadening, the accurate evaluation of the line shape permitted a separate determination of the physical conditions of the plasma. In fact, this diagnosis was feasible only because of this comparison with a sophisticated code calculation of the line profile. The difficulties addressed in the computation included not only the uncertainties associated with the instrument width, but also the problems that arose in the line wings from the appearance and possible merging of satellite forbidden transitions and contributions from other ionization stages or impurities.

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