Density diagnostic of a uranium laser-produced plasma from the line ratio of $\Delta n = 1$ transitions in Ni-like uranium

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The intensity ratio of the electric quadrupole $3p^63d^{10}$-$3p^5_{3/2}4f_{7/2}(J=2)$ line to the electric dipole $3p^63d^{10}$-$3p^5_{1/2}4s$ line is used as a density diagnostic of a highly ionized uranium laser-produced plasma for electron densities of 10^{19}-10^{23} cm^{-3}. Calculations show that this ratio is insensitive to the plasma temperature in the range of 1000–4000 eV. Self-absorption of the lines is shown to be unimportant in this density range. Experimental line ratios are compared to the predictions of a Ni-like uranium-ion model that includes 138 excited levels. The densities inferred from this analysis applied to a measured line ratio yield densities of $(4.0\pm0.5)\times10^{22}$ cm^{-3}. This is in good agreement with models of x-ray production in laser-produced plasmas.

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I. INTRODUCTION

The spectra of highly ionized heavy elements ($Z>70$) obtained from laser-produced plasmas are often dominated by the electric dipole resonance lines of the isoelectronic sequence of nickel. The transitions from the $J=1$ odd-parity levels $3d^94p$, $3d^94f$, $3d^95f$, $3p^54s$, and $3p^54d$ to the ground state $3p^63d^{10}$ have been observed in most of the elements from the rare earths to uranium [1–11]. More recently, density-sensitive electric-quadrupole decays have been observed in laser-produced plasmas from tantalum ($Z=73$) to mercury ($Z=80$) [12]. In Ref. [12], space-resolved intensity measurements of these $3p$-$4f$ lines were used to determine the electron density as a function of position. Good qualitative agreement with theoretical predictions was achieved. The analysis of the spectrum from a uranium laser-produced plasma [11] and the identification of the rather intense electric quadrupole $3p^63d^{10}$-$3p^5_{3/2}4f_{7/2}(J=2)$ transition prompted us to explore the use of this line as an electron-density diagnostic of the plasma.

II. EXPERIMENT

A uranium laser-produced plasma was generated using the Nova laser facility at the Lawrence Livermore National Laboratory. A one-nanosecond pulse of 0.35-μm wavelength light from a single beam of the laser was focused to an intensity of 7×10^{14} W/cm^2 onto a thick disk of uranium. The spectrum was recorded with a time- and space-integrating Bragg crystal spectrograph. A detailed account of the experiment can be found in Ref. [11]. Figure 1 shows a 0.2-Å portion of the measured x-ray spectrum in the region of interest. Three Ni-like lines are present in this wavelength range. These are two electric dipole lines $3p^63d^{10}$-$3p^5_{3/2}4d_{5/2}(J=1)$, labeled A at $\lambda=2.984$ Å, and $3p^63d^{10}$-$3p^5_{1/2}4s(J=1)$ labeled B at $\lambda=2.862$ Å. The third line is an electric quadrupole transition $3p^63d^{10}$-$3p^5_{3/2}4f_{7/2}(J=2)$ labeled Q at $\lambda=2.819$ Å. The measured ratios of the line intensities are $I_Q/I_A=0.4\pm0.1$ and $I_Q/I_B=2.0\pm0.5$.

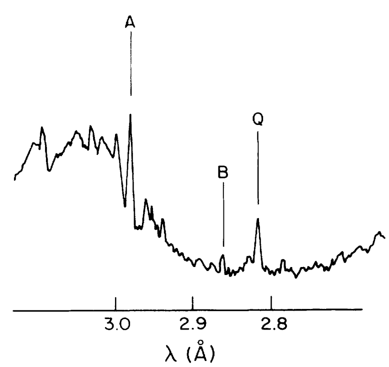

FIG. 1. Experimental spectrum of a uranium laser-produced plasma in the 2.8–3.0-Å range. Lines A, B, and Q are the $3p^63d^{10}$-$3p^5_{3/2}4d_{5/2}(J=1)$, $3p^63d^{10}$-$3p^5_{1/2}4s(J=1)$, and $3p^63d^{10}$-$3p^5_{3/2}4f_{7/2}(J=2)$ transitions in Ni-like uranium.

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III. THEORY

A model of the Ni-like ion has been developed using the HULLAC atomic-physics package [13,14]. The atomic structure is calculated using the relativistic-multiconfiguration-parametric-potential method. Radiative electric-dipole and electric-quadrupole transitions between all the levels were calculated. Collisional rates were calculated using the quasirelativistic distorted-wave method [15]. The model included 139 levels from the following configurations: $3s^2 3p^6 3d^{10}$, $3s3p^6 3d^{10} 4l$, $3s^2 3p^5 3d^{10} 4l$, $3s^2 3p^6 3d^9 4l$ ($l = s, p, d$, or f), $3s^2 3p^6 3d^9 5p$, and $3s^2 3p^6 3d^9 5f$. Self-absorption of the lines has been taken into account in the present work using a simple escape-factor treatment [16,17]. This involves a correction to the Einstein coefficients appearing in the rate equations by

$$A_{ij} \rightarrow \epsilon_{ij} A_{ij} .$$

The "escape factor" ϵ_{ij} is given by

$$\epsilon_{ij} = (1/\tau_{ij}\sqrt{\pi}) \int_{-\infty}^{+\infty} \{1 - \exp[-\tau_{ij} \exp(-y^2)]\} dy ,$$

where the optical depth at line center for the transition $j \rightarrow i$ is

$$\tau_{ij} = (\pi e^2 2\sqrt{\ln 2}/mc\sqrt{\pi}) f_{ij} n_i L / \Delta_D(T_i) . \quad (1)$$

The Doppler width at the ion temperature T_i is $\Delta_D(T_i)$, f_{ij} is the oscillator strength of the transition, n_i is the population density of the absorbing state, and L is the half width of the plasma column. The coupled quantities n_i and ϵ_{ij} were determined by iteratively solving the rate equations until the level populations converged. This is an approximation of the effects of self-absorption which ignores the effects of density, temperature, and velocity gradients in the plasma.

One estimate of the relevant electron temperature was made using a flux-limit approximation which balances the laser-absorption rate and rate of heat conduction at the critical surface, $n_c = 9 \times 10^{21}$ cm^{-3} (Ref. [18]). This approximation results in the expression

$$T_e(\text{keV}) = 0.6(I\lambda^2/f)^{2/3} , \quad (2)$$

where I is the absorbed laser intensity in units of 10^{14} W/cm^2, λ is the laser wavelength in μm, and f is the flux limiter. For the parameters in the present experiment, using $f = 0.08$ (Ref. [19]) results in $T_e = 2.9$ keV. This estimate is consistent with the calculated coronal temperature from hydrodynamic code simulations of a gold disk [20]. These and other similar simulations show that the emission of $n = 4$ to 3 transitions originates from a region spanning the temperature range of from 1 keV in the ablation region to 3 keV in the corona. The simulation indicates that the peak emission is located in the ablation region where the density varies from 1 to 7×10^{22} cm^{-3} at an electron temperature near 1 keV.

Since the ionization potential of U^{64+} is 7.39 keV and of U^{63+} is 4.6 keV and in view of the preceding arguments, computations have been performed at two extremes in temperature, $T_e = 1$ and 4 keV. The first calculations of the ratio of the quadrupole transition to the two dipole transition line intensities as a function of the electron density, I_Q/I_A and I_Q/I_B, were performed in the optically thin limit. The results are shown in Fig. 2. Both line ratios are insensitive to temperature in this limit. The results in Fig. 2 indicate that the ratio I_Q/I_A appears to be a useful diagnostic of electron density for densities between $10^{21}-10^{23}$ cm^{-3}, while the ratio I_Q/I_B is applicable in the density range between $10^{19}-10^{23}$ cm^{-3}.

Additional calculations were performed to estimate the effects on the line ratio of self-absorption of the lines. These effects are specific to a particular experiment and require detailed information on the plasma conditions: T_i, n_i, and L. Since none of these parameters was independently determined, approximate values can give an indication of the sensitivity of the line ratios to self-absorption. For these calculations we have assumed that $T_i = T_e/2$. The spatial scale, $L = 200$ μm, corresponds to the radius of the laser focal spot and is also the distance the coronal plasma has expanded at the end of the laser pulse. The latter was measured from time-resolved images of $n = 4$ to 3 and 5 to 3 transitions from a gold plasma. The density of absorbing species, as expressed in terms of the fractional abundance of Ni-like ions, f_{Ni}, was assumed to be 0.1 or 0.2.

The I_Q/I_B ratio was found to be unaffected by self-absorption. This is a result of the small oscillator strengths for these transitions, $f_B = 0.044$ and $f_Q = 0.018$. Therefore, these calculations indicate that this ratio is a useful density diagnostic in the range $10^{19}-10^{23}$ cm^{-3}. The results for the I_Q/I_A ratio are shown in Fig. 3. It is obvious that the I_Q/I_A ratio is dependent on these other parameters, and thus self-absorption can be important. This is a result of the larger oscillator strength of the A line, $f_A = 1.35$. At 1 keV, the ratio is no longer monotonic with the density, resulting in a totally unreliable density diagnostic. At 4 keV, the line-intensity ratio remains a monotonic function of density, but the magnitude of the ratio is dependent on the density of the absorbing species. Actually, the ratio will depend on $n_i L$ as in Eq. (1), but we have fixed L in this set of calculations.

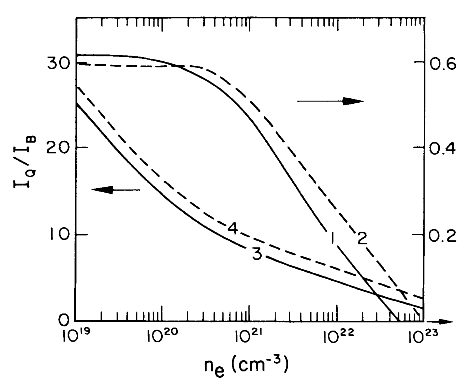

FIG. 2. Theoretical intensity ratios of the $3p$-$4f$ (Q) $E2$ transition to $3p$-$4d$ (A) and $3p$-$4s$ (B) $E1$ transitions as functions of electron density in the optically thin limit. The curves are (1) I_Q/I_A, $T_e = 1$ keV, (2) I_Q/I_A, $T_e = 4$ keV, (3) I_Q/I_B, $T_e = 1$ keV, and (4) I_Q/I_B, $T_e = 4$ keV.

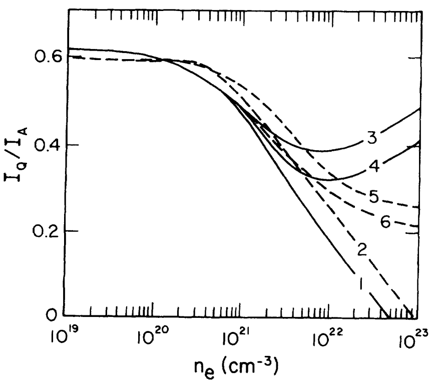

FIG. 3. Theoretical intensity ratios of the $3p$-$4f$ (Q) $E2$ transition to the $3p$-$4d$ (A) $E1$ transition as a function of electron density. Two of the curves are (1) I_Q/I_A, $T_e=1$ keV, and (2) I_Q/I_A, $T_e=4$ keV. Both are calculated in the optically thin limit (identical to Fig. 2, curves 1 and 2). The remaining curves include the effects of self-absorption on I_Q/I_A for $L=200$ μm: (3) $T_e=1$ keV and $f_{\rm Ni}=0.1$, (4) $T_e=1$ keV and $f_{\rm Ni}=0.2$, (5) $T_e=4$ keV and $f_{\rm Ni}=0.2$, and (6) $T_e=4$ keV and $f_{\rm Ni}=0.1$.

IV. RESULTS

The results of the calculations can be compared to the measurements of the line ratios. From Fig. 2 the inferred density from the I_Q/I_B ratio of 2.0 ± 0.5 is $(4.0\pm0.5)\times10^{22}$ cm^{-3} at an electron temperature of 1 keV and $(8.2\pm1.0)\times10^{22}$ cm^{-3} at an electron temperature of 4 keV. The I_Q/I_A ratio is strongly affected by self-absorption. As a result, for the present experiment we can only hope to find a reasonable set of conditions that are consistent with the density inferred from the I_Q/I_B ratio. It is obvious from Fig. 2 that the inferred density from the I_Q/I_A ratio is inconsistent with the assumption of optically thin emission since it yields an electron density between $0.7-3.4\times10^{21}$ cm^{-3} at an electron temperature of 1 keV and $0.9-6.0\times10^{21}$ cm^{-3} at an electron temperature of 4 keV which is approximately an order of magnitude lower than the I_Q/I_B ratio. Self-absorption effects are important. The effects of self-absorption and the uncertainties in the measured line-intensity ratio result in large uncertainties in the inferred density. In this particular application, the I_Q/I_A ratio is useless as a density diagnostic. It is useful to note that the density inferred from curves 3 and 4 in Fig. 3, which assume an electron temperature of 1 keV and $f_{\rm Ni}=0.1$ and 0.2 respectively, overlap with the inferred density from the I_Q/I_A ratio. Relying on the I_Q/I_B ratio only, the inferred electron density at $T_e=2$ keV is $(4.0\pm1.5)\times10^{22}$ cm^{-3}. This density compares quite well with simulations which give a range of $(1-7)\times10^{22}$ cm^{-3} for the expected electron density.

It should be pointed out that the I_Q/I_B ratio could not be used by the authors in Ref. [12]. The B line was not identified in their spectra of lower Z elements. Also, in the case of lower Z elements, the wavelength separation between B and Q is much larger. Better agreement between theory and experiment could probably be achieved in this work by increasing the electron temperature or lowering the fractional abundance of Ni-like ions in the model.

V. CONCLUSIONS

The intensity ratio of the electric quadrupole $3p^6 3d^{10}$-$3p^5_{3/2}4f_{7/2}(J=2)$ line to the electric dipole $3p^6 3d^{10}$-$3p^5_{1/2}4s$ line can be used to give a density diagnostic of a highly ionized uranium laser-produced plasma for electron densities of $10^{19}-10^{23}$ cm^{-3}. Calculations show that this ratio is almost insensitive to the plasma temperature in the range of 1–4 keV. Self-absorption effects are also shown to be unimportant in this density range for 200-μm scale plasmas. The densities inferred from this analysis applied to a measured line ratio, yield densities greater than critical for 0.35-μm wavelength laser light: the inferred electron density at $T_e=1$ keV is $(4.0\pm0.5)\times10^{22}$ cm^{-3}. This is in agreement with calculational models of x-ray production in laser produced plasmas. The ratio of the quadrupole transition to the $3p^6 3d^{10}$-$3p^5_{3/2}4d_{5/2}(J=1)$ transition is strongly affected by self-absorption for the conditions encountered in this study and is useless as a density diagnostic.

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