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Measurements of gain and line broadening in lithiumlike aluminum

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Spectroscopic measurements were made of lithiumlike Al emission lines from laser-produced plasmas. Flat targets, consisting of thin layers of Al coated on a Mylar backing, were irradiated with up to eight beams of the OMEGA laser system employing a line-focus configuration. The Al XI $4f$-$3d$ line at 154.7 Å exhibited a gain coefficient of 4.1 ± 1.2 cm^{-1} from comparisons of line intensities from 3- and 6-mm-long plasmas. Similarly, the $4d$-$3p$ line at 150.7 Å and the $5f$-$3d$ line at 105.7 Å had gain coefficients of 4.5 ± 1.3 and 3.5 ± 0.8 cm^{-1}, respectively. The linewidth of the $5f$-$3d$ line was measured to be 0.35 Å, which is much larger than the expected Doppler and instrumental width and can be attributed to Stark broadening. This Stark broadening corresponds to an electron density of 3×10^{19} cm^{-3}.

Laser-produced plasmas have been extensively studied as a medium for producing xuv and x-ray laser systems. Using three-body recombination in a dense plasma to produce an x-ray laser was first proposed by Gudzenko and Shelepin.[1] In order for this method to work, the plasma must be ionized past the ionization stage where inversion occurs. Then as the plasma cools and recombines, higher n (quantum-number) levels become populated preferentially, leading to population inversions. Much progress has been made in using the recombination phase of a plasma to create a population inversion in selected ions. Early experimental work showed population inversion in C VI.[2,3] Suckewer *et al.*[4] used a recombining, cylindrical plasma to demonstrate amplification and gain ($G=6.5$ cm^{-1}) in the 182-Å line of C VI. A great deal of computational modeling of a plasma with recombination into hydrogenlike ions has been developed by Pert.[5,6]

In Li-like ions, the $4f$-$3d$ and $5f$-$3d$ lines have both exhibited gain in various experiments. An early experiment using a Nd:glass laser of intensity $(1-2)\times10^{13}$ W/cm^2 indicated inversion of the $n=4$ and 5 levels of Al XI relative to the $n=3$ level.[7] The populations were deduced from measurements of the nd-$2p$ transitions allowing for self-absorption. Extensive study of the $5f$-$3d$ line of Al XI at 105.7 Å has been performed by Jaegle *et al.* using a line-focused Nd:glass laser irradiating a slab target.[8,9] Amplification of this line with a gain-length product of 2–2.5 was observed. Suckewer *et al.*, using a CO$_2$ laser, showed evidence for population inversion in the $4f$-$3d$ lines of O VI and Ne VIII.[10] In later experiments, also using a CO$_2$ laser, the Al XI and Si XII $4f$-$3d$ transitions exhibited population inversion and gain.[11]

In our experiment we have recorded high-resolution, time-integrated spectra of highly ionized, cylindrical Al plasmas. The $4f$-$3d$ (154.7-Å), $4d$-$3d$ (150.7-Å), and the $5f$-$3d$ (105.7-Å) lines of Li-like Al exhibited gain upon increasing the length of the plasma column. Measurements of spectral linewidths of these transitions will also be discussed.

Cylindrical plasmas were produced for these measurements by using up to eight line-focused beams from the OMEGA Nd:glass laser system at a wavelength of 351 nm. A schematic of the experimental setup is shown in Fig. 1. Typical pulse lengths were 650 ps, while the laser irradiance was 8×10^{13} W/cm^2. Each beam focused to a spot approximately 1.5 mm long and 100 μm wide, using an $f/3.7$ fused-silica lens combination consisting of a high-power aspheric singlet lens and a closely coupled cylindrical corrector plate. Flat targets, employed for these measurements, consisted of a 0.5-μm layer of Al and a 0.01-μm layer of Au on a 10-μm-thick Mylar backing. The gold layer was included in order to provide additional radiative cooling, which perhaps could enhance the population inversion through faster recombination. A cooling effect from the addition of gold layers in spherical targets undergoing uniform laser irradiation has been observed previously.[12] However, in this case the addition of a gold layer did not appreciably change the relative line intensities compared to only an aluminum layer and therefore did not have a significant effect on our results. In this laser setup both sides of the target were illuminated by equal symmetric beams. Since the target was thicker than the burn-through depth, essentially separate plasmas were created on each side of the target. One plasma consisted of mainly aluminum ions while the other plasma (Mylar) consisted of carbon and oxygen ions. In Fig. 2 we show a contour plot of x-ray emission from the plasma taken by an x-ray pinhole camera (using two pinholes for two images). A thin (25-μm) Be filter was employed producing images in the 0.8–1.5-keV range. Note that although eight beams were used, only the four beams ir-

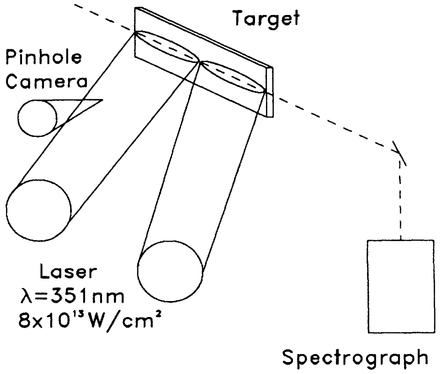

FIG. 1. Experimental setup showing line-focus arrangement.

radiating the aluminum side of the target produced the plasma for our measurements. The gain occurs later in time when the plasma has expanded and is believed to be more uniform than is indicated from the x-ray images in Fig. 2.

A 3-m grazing-incidence spectrograph was used to record spectra on Kodak 101-05 photographic plates in the range 30–300 Å.[13] Targets were precisely positioned relative to the spectrograph so that the spectrograph viewed along the axis of the cylindrical plasma. The emission was focused onto the entrance slit of the spectrograph by a grazing incidence mirror. The entrance slit and the surface of the focusing mirror were rotated approximately 1° with respect to each other (around the cylindrical axis) allowing spatial imaging of the spectral emission. Spectra from both the aluminum plasma and the Mylar plasma were observed on a photographic plate.

In a medium in which radiation is amplified over a length L, the monochromatic intensity of the radiation is given by

$$I=S(e^{GL}-1)\ , \tag{1}$$

where S is the source function and G is the gain coefficient. If l_1 and l_2 are lengths of two plasma columns, then the ratio of intensities is

$$\frac{I_2}{I_1}=\frac{(e^{Gl_2}-1)}{(e^{Gl_1}-1)}\ . \tag{2}$$

Therefore, one can solve for G from line-intensity measurements at two lengths. Spectral measurements were made here for two lengths of line focus, 3 and 6 mm. For the 3-mm line focus, 2 beams (aligned axially) irradiated each side of the target, while for the 6-mm line focus, four beams irradiated each side. The Al spectra contained emission lines of ionization states up to He-like Al, with Li-like Al showing the most prominent lines. Figures 3(a) and 4(a) show spectra containing the $4f$-$3d$, $4d$-$3p$, and $5f$-$3d$ lines of Li-like Al for a plasma length of 3 mm, while Figs. 3(b) and 4(b) show the same spectral regions for a 6-mm plasma length. One can see in these figures that the $4f$-$3d$, $4d$-$3p$, and $5f$-$3d$ lines show a larger relative increase than other nearby lines, when the plasma length is doubled. The $5d$-$3p$ line is observed but appears to be blended with other lines and no gain can be measured. The relative increase of the peak intensities of the $4f$-$3d$, $4d$-$3p$, and $5f$-$3d$ lines on doubling the plasma length was determined by comparing these lines to other lines in the same spectra for which no gain is expected. This method greatly reduces shot-to-shot variations in the response of the photographic plates. Using this relative calibration and averaging over several shots, the gain coefficients were determined to be $G=4.1\pm1.2\ \text{cm}^{-1}$ for the $4f$-$3d$ line, $G=4.5\pm1.3\ \text{cm}^{-1}$ for the $4d$-$3p$ line, and $G=3.5\pm0.8\ \text{cm}^{-1}$ for the $5f$-$3d$ line. The gain coefficient for the $5f$-$3d$ line indicates a large population in the $5f$ level, which will be discussed later. The $3d$-$2p$ transition shows an increase in intensity slightly less than would be expected from doubling the plasma length. This transition would have the largest optical thickness due to the relatively large oscillator strength and the large population of the $n=2$ level. Significant absorption in the $3d$-$2p$ transition also in the radial direction would limit the population inversion possible for the higher n levels.

The width of the lines showing gain is an important

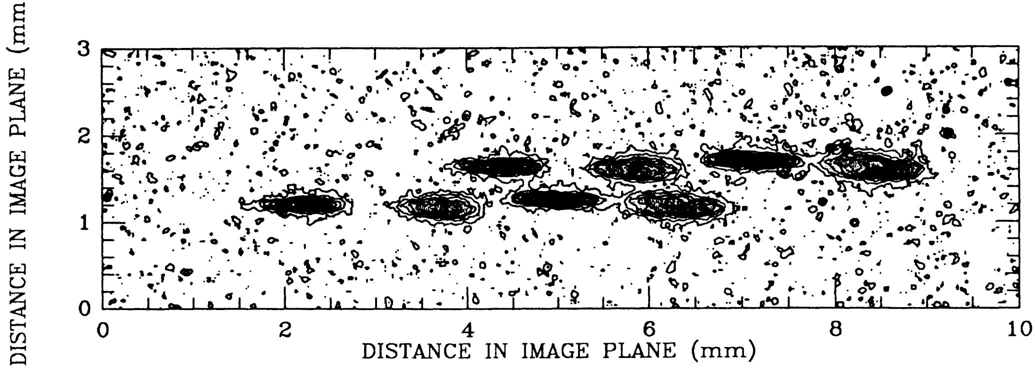

FIG. 2. Contour plot of the x-ray emission from a line-focus plasma. Two pinholes were used to record two images of the plasma on the same film. In this case four beams irradiated each side of the target.

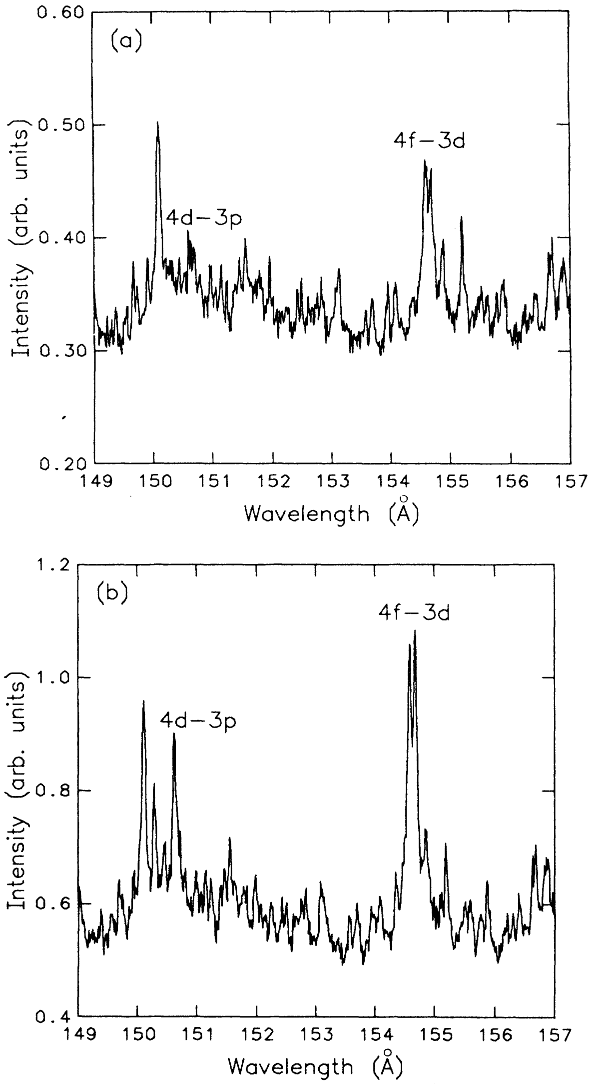

FIG. 3. Spectra showing the $4d$-$3p$ and $4f$-$3d$ lines of Li-like aluminum. (a) 3-mm line focus. (b) 6-mm line focus.

quantity since the gain coefficient is directly related to the linewidth (assuming a Gaussian profile) through the expression[14]

$$G=2(\pi \ln 2)^{1/2}\frac{e^2}{mc^2}\frac{\lambda^2 f}{\Delta\lambda}\left[N_u-\frac{g_u}{g_l}N_l\right], \quad (3)$$

where e is the electron charge, m is the mass of an electron, c is the speed of light, λ is the wavelength, f is the emission oscillator strength, $\Delta\lambda$ is the linewidth, N_u and N_l are the densities of the upper and lower states, respectively, and g_u and g_l are the statistical weights. The linewidths of the $4f$-$3d$, $4d$-$3p$, and $5f$-$3d$ lines were measured by fitting a Gaussian curve to the measured line profile. Large broadening ($\Delta\lambda=0.35$ Å) was observed for the $5f$-$3d$ line. Our measurements for the $4f$-$3d$, $4d$-$3p$, and $5f$-$3d$ transitions are listed in Table I.

We have also calculated the quantity $\Delta N=N_u-(g_u/g_l)N_l$ which is a measure of the population inversion. Inserting the measured linewidths and gains into Eq. (3) we solve for ΔN for the transitions where gain is observed. The values are listed in Table I. Although the population inversion for the $5f$ level is much larger than that for the $4f$ level, the actual population of the $5f$ level may be only slightly higher if the $3d$ level has a population $\geq 10^{17}$ cm^{-3}. This value is not unreasonable since a time-independent collisional-radiative model (including only excitation and radiative decay) would predict a population of $\sim 10^{17}$ cm^{-3} for the $3d$ level if the total density of Li-like Al is assumed to be 5×10^{18} cm^{-3}. A detailed time-dependent model including ionization and recombination processes is being developed to model these plasma conditions, since the large population of the $n=4$ and 5 levels occurs when the plasma is cooling and recombining. Mixing of the $5f$ and $5g$ levels which are very closely spaced may also contribute to the large gain observed for the $5f$-$3d$ transition.

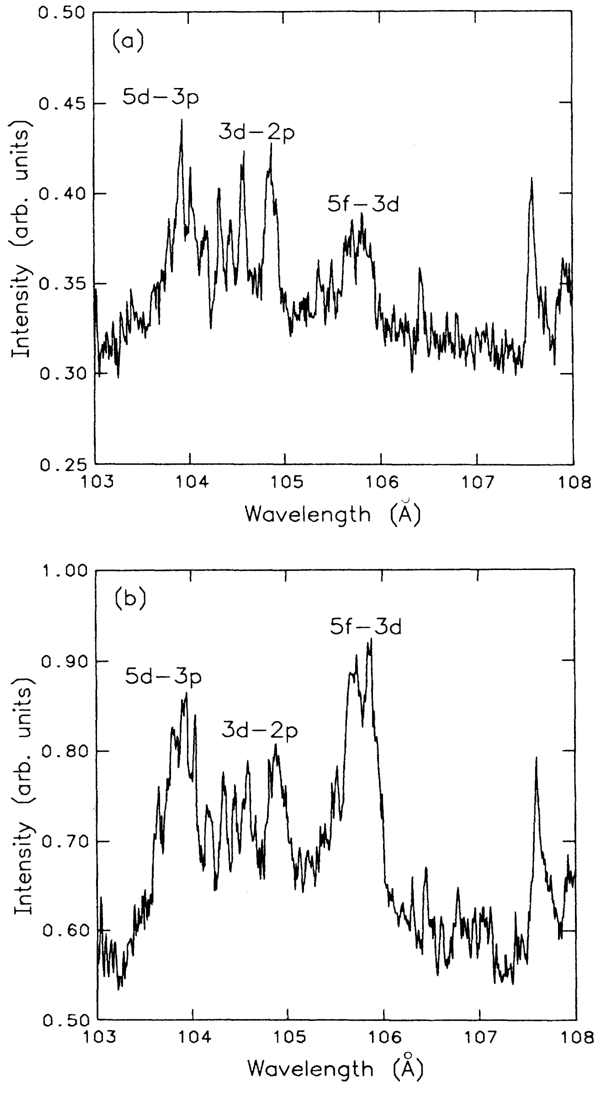

FIG. 4. Spectra showing the $5d$-$3p$ and $5f$-$3d$ lines of Li-like aluminum. (a) 3-mm line focus. (b) 6-mm focus.

TABLE I. Experimental results.

Transition	λ (Å)	G (cm^{-1})	$\Delta\lambda$ (Å)	ΔN (cm^{-3})
$5f$-$3d$	105.7	3.5 ± 0.8	$0.35^{a}\pm0.05$	$(1.2\pm0.3)^{b}\times10^{17}$
$4f$-$3d$	154.7	4.1 ± 1.2	$0.04^{a}\pm0.01$	$(1.1\pm0.4)^{b}\times10^{15}$
$4d$-$3p$	150.7	4.5 ± 1.3	$0.04^{a}\pm0.01$	$(2.7\pm0.7)^{c}\times10^{15}$

[a] Corrected for instrumental broadening.

[b] For the $J=\frac{7}{2}$ to $J'=\frac{5}{2}$ transition.

[c] For the $J=\frac{5}{2}$ to $J'=\frac{3}{2}$ transition.

Let us examine the linewidth of the $5f$-$3d$ line (105.7 Å) in more detail. Assuming an upper limit for the temperature of Li-like ions of 200 eV, we get an expected Doppler width of ≤ 0.02 Å, which is much less than the measured width. The instrumental contribution to the linewidth is ≤ 0.04 Å and is therefore also negligible in this case. We attribute the large linewidth measured to Stark broadening. To test the consistency of this assumption we can calculate the electron density N_e, using theoretical calculations for Stark broadening.[15,16] The linewidth is given by

$$\Delta\lambda = 2F_0\alpha_{1/2}\left[\frac{2}{Z}\right]^5 , \tag{4}$$

where Z is the atomic number, $\alpha_{1/2}$ is computed by Kepple[15] for $Z=2$ (ionized helium), and F_0 is given by the expression

$$F_0 = 1.25\times10^{-9}N_e^{2/3}\bar{Z}^{\,1/3} , \tag{5}$$

where $\bar{Z}$ is the average ionic charge. For the $n=5-3$ transition of Al XI we use $\alpha_{1/2}=3.2\times10^{-2}$. This yields an electron density of $N_e=(3.3\pm0.7)\times10^{19}$ cm^{-3}. This value for N_e is consistent with the estimated values for the population of the excited levels of Li-like Al that show inversion. The linear theory of Stark broadening does not apply for the $4f$-$3d$ transition because the nl-nl' level splitting is larger than the linewidth.

In summary, we have observed population inversion and gain in $4f$-$3d$, $4d$-$3p$, and $5f$-$3d$ transitions in laser-produced plasmas by varying the length of the plasma column. These observations of gain were obtained despite the fact that our measurements were time integrated, which indicates that most of the emission from these transitions occurs when the plasma is recombining. These results support earlier measurements made by Jaegle *et al.*[8,9] In addition, we have measured the linewidths of these transitions and observed increased, broadening in the $5f$-$3d$ transition due to Stark broadening.

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