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Saturation and Kinetic Issues for Optical-Field-Ionized Plasma X-Ray Lasers

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Abstract

Lasing between excited states and the ground state following optical-field ionization is studied. Saturation of an x-ray laser when the lower lasing level is a ground state of a H-like or Li-like ion is discussed. Efficiencies of 10^{-5} to 10^{-4} are calculated for the $3d_{5/2} - 2p_{3/2}$ transition at 98 Å in Li-like Ne. The assumption that the fine-structure levels are populated according to their statistical weights is shown to be justified through comparisons with calculations using a detailed atomic model. The effect of saturation by a given fine-structure transition on the populations of the fine-structure levels is analyzed.

I. Introduction

Optical-field ionization by a high-intensity/short-pulse UV laser allows the possibility of x-ray lasing between excited states of an ion and the ground state.[1,2] We calculate efficiencies in Li-like Ne, for the $3d_{5/2} - 2p_{3/2}$ transition at 98 Å, to be in the range of 10^{-5} to 10^{-4}. These relatively high efficiencies are obtained despite the short lifetime of this self-terminating laser and the reduced saturation intensity associated with the lower lasing state being the ground state of the ion. In this proceeding we discuss saturation issues for lasing down to the ground state in H-like and Li-like ions. A common assumption in modeling these ions is that the fine-structure levels are populated according to their statistical weights. We discuss the validity of this approximation by comparing shell-averaged results with those obtained using a detailed atomic model. We also study the effects of saturation on the relative population of the fine-structure levels.

II. Saturation Issues for Lasing to Ground State

The large energy difference between the ground state and the first excited state of an ion makes the idea of lasing down to the ground state an attractive one. The small populations that can be achieved in excited states require that the ground state be emptied to a very high degree (of order 0.1%) to obtain population inversion and gain. Such complete ionization appears possible by using high-intensity lasers where the electric field associated with the laser field is larger than the Coulomb field binding the ground-state electrons, of a given ionization stage, to the nucleus.[1,3] If the electron temperature following ionization is sufficiently low, there is rapid collisional recombination to the upper levels followed by collisional cascade giving large population inversions and gains between the first excited state and the ground state. The ground state is populated on a time scale associated with the radiative lifetime of the first excited state which is of order a picosecond. The short lifetime of these self-terminating lasers reduces the energy that can be obtained. An additional aspect of lasing down to the ground state that limits the output energy is the relatively low intensity required to saturate.

As the length of the lasing medium is increased the output increases exponentially until the intensity associated with the lasing transition starts to affect the kinetics. The intensity at which the gain is reduced to 1/2 the small-signal-gain value is referred to as the saturation intensity I_{sat}. For transitions between excited states, one can often neglect the effect of the intensity on the lower laser state population in calculating saturation.[4] In this case, I_{sat} is the intensity that causes the upper laser state to be reduced by a factor of 2. This is found by equating the stimulated rate out of the upper laser state with the total exit rate γ_{out} excluding stimulated processes. For lasing down to the ground state, one cannot neglect the effect of the intensity on the lower laser state for two reasons. First, electrons stimulated out of the upper laser state accumulate in the lower state. Second, the population inversion at the time of maximum gain is not large which results in the gain being sensitive to the population in the lower laser state. We first show how to calculate I_{sat} neglecting fine-structure levels and then discuss the role of fine structure in H-like and Li-like ions.

In treating the situation where the lower laser state cannot be neglected, we introduce a parameter α whose value will depend on the populations and statistical weights of the lasing levels. We equate the net stimulated emission out of the upper laser state to α times γ_{out},

$$\frac{c^2}{2h\nu^3}A_{ul}\left(1-\frac{N_l' g_u}{N_u' g_l}\right)J_{sat}=\alpha\gamma_{out}, \qquad (1)$$

where $(1 - N_l' g_u/N_u' g_l)$ is the population inversion factor, primes denote saturated values, g_u and g_l are the statistical weights of the upper and lower states, respectively, A_{ul} is the spontaneous emission rate, and J_{sat} is the specific (or per unit frequency) mean saturation intensity. The population of the upper level is reduced as a result of saturation because of the additional exit channel via stimulated emission. By equating the population outward flow without stimulated emission $N_u\gamma_{out}$ to the outward flow after saturation $N_u'\gamma_{out}+N_u'\alpha\gamma_{out}$, the saturated population can be expressed in terms of the population in the absence of stimulated processes as $N_u' = N_u/(1+\alpha) = \beta N_u$, where $\beta \equiv 1/(1+\alpha)$. Assuming that electrons that arrive in the lower state accumulate there, the saturated population in the lower state is $N_l' = N_l + (1-\beta)N_u$. This is usually a good approximation when the lower laser state is a ground state of the ion. We can solve for β by requiring that the gain calculated using N_u' and N_l' be 0.5 times the small-signal gain giving

$$\beta=\left[\frac{1}{2}\left(1+\frac{N_l g_u}{N_u g_l}\right)+\frac{g_u}{g_l}\right]\Big/\left(1+\frac{g_u}{g_l}\right). \qquad (2)$$

Using this expression for β and then α from $\alpha = 1/\beta - 1$, we obtain J_{sat} from Eq. (1). The saturated intensity is then given by $I_{sat} = \Delta\nu J_{sat}(2\pi^3/ln2)^{1/2}$, where $\Delta\nu$ is the FWHM of the atomic line profile.

As an example of the effect of including the lower state, the choice $N_l g_u/N_u g_l = 1/2$ and $g_u/g_l = 2.25$ gives $\alpha = 0.09$. This results in a factor of 12 decrease in I_{sat} as compared with neglecting the role of the lower state in determining the intensity sufficient to saturate the laser. This ratio of the statistical weights corresponds to the $n = 3$ to $n = 2$ levels in a Li-like ion neglecting fine structure. For lasing down to the ground state of a H-like ion from the first excited state, $g_u/g_l = 4$ and $\alpha = 0.05$ for the same amount of inversion. In general, the spacing between fine-structure levels is greater than the line widths and the effects of fine structure must be included in calculating saturation.

The assumption that the fine-structure levels are populated according to their statistical weights allows an easy estimate of the role of fine structure on saturation. We address the validity of this approximation in the next section. In Li-like ions, the $3d_{5/2} - 2p_{3/2}$ is the fine-structure transition between the $n = 3$ and $n = 2$ levels with the largest gain and therefore it reaches saturation first. The A_{ul} rate used in Eq. (1) is for this fine-structure transition, but we continue to use the shell-averaged or total exit rate γ_{out}. The population outward flow without stimulated emission is $N_{n=3}\gamma_{out} = 3N_u\gamma_{out}$, where N_u is the population of the $3d_{5/2}$ level which has 1/3 of the $n = 3$ population if the sublevels are populated according to their statistical weights. Equating this to the outward flow after saturation, $3N_u'\gamma_{out} + N_u'\alpha\gamma_{out}$, one obtains an expression for N_u' given by $N_u' = N_u/(1+\alpha/3) = \tilde{\beta}N_u$, where $\tilde{\beta} \equiv 1/(1+\alpha/3)$. Assuming the $n = 2$ levels are populated according to their statistical weights, 1/2 of the electrons stimulated out of the upper laser level accumulate in the $2p_{3/2}$ lower laser level. This gives $N_l' = N_l + 1/2(1-\tilde{\beta})N_u$ and solving for $\tilde{\beta}$ one obtains

$$\tilde{\beta} = \left[\frac{1}{2}\left(1 + \frac{N_l g_u}{N_u g_l}\right) + \frac{1}{2}\frac{g_u}{g_l}\right] \Big/ \left(1 + \frac{1}{2}\frac{g_u}{g_l}\right). \tag{3}$$

For $N_l g_u/N_u g_l = 1/2$ and $g_u/g_l = 6/4 = 1.5$, appropriate for the $3d_{5/2} - 2p_{3/2}$ transition, $\alpha = 0.5$. If the lower state is neglected in calculating saturation, $\alpha = 3$ because the stimulated rate acts only on the $3d_{5/2}$ population. Thus including the lower state results in a factor of 6 decrease in I_{sat} for $N_l g_u/N_u g_l = 1/2$.

In H-like ions, the $2p_{3/2} - 1s_{1/2}$ transition has the largest gain and saturates first. The $2p_{3/2}$ level has 1/2 of the $n = 2$ population if the sublevels are populated according to their statistical weights and we have $N_u' = N_u/(1+\alpha/2) = \hat{\beta}N_u$ and $N_l' = N_l + (1-\hat{\beta})N_u$. These are the same expressions as for the first case where fine structure is neglected with $\hat{\beta}$ replacing β. The expression for β, Eq. (2), can be used for $\hat{\beta}$ with $\alpha = 2(1/\hat{\beta} - 1)$. For $N_l g_u/N_u g_l = 1/2$ and $g_u/g_l = 2$, appropriate for the $2p_{3/2} - 1s_{1/2}$ transition, $\alpha = 0.18$ which is a factor of 11 decrease as compared with neglecting the lower state population. For comparable population inversions, the $2p_{3/2} - 1s_{1/2}$ transition in H-like ions has a greater reduction in I_{sat}, associated with including the lower laser state, than the $3d_{5/2} - 2p_{3/2}$ transition in Li-like ions.

We calculate reasonable efficiencies for the $3d_{5/2} - 2p_{3/2}$ transition in Li-like Ne despite the short duration of lasing and the reduction in I_{sat} associated with the lower laser state being the ground state. In Fig. 1 we show the calculated efficiencies (output energy/input energy) at an electron density of 2.5×10^{20} cm^{-3} as a function of electron temperature T_e for three laser focal radii. The increase in efficiency as T_e decreases is because of more rapid recombination and collisional cascade to the upper laser level. The increase in efficiency with increasing radius comes from the assumption that the length of the lasing region is given by

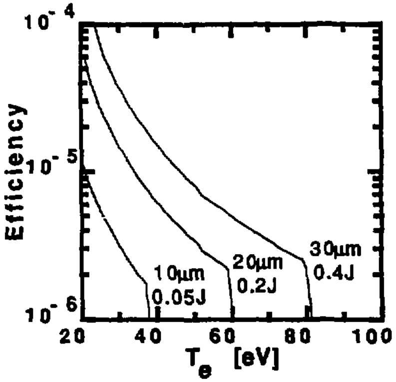

Figure 1: Efficiency versus temperature at an electron density of 2.5×10^{20} cm^{-3} for several values of focal radius and the corresponding input energy.

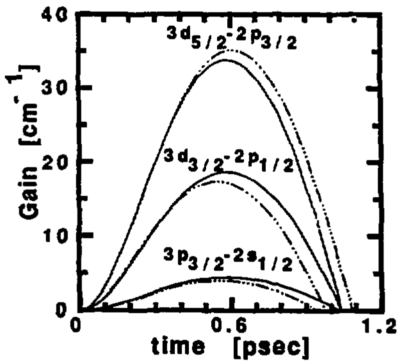

Figure 2: Small-signal gains calculated with independent sublevels (solid curves) and with sublevels populated according to their statistical weights (dashed curves).

the confocal length $z = 4\pi a^2/\lambda ln2$, where λ is wavelength of the driving laser and a is the half-intensity focal radius. Refraction arising from transverse ionization gradients can limit the length of the laser and we are studying the effects of a preionized channel and imposed density gradients to control refraction. We have calculated efficiencies as high as 10^{-4} by using an electron density of 1.0×10^{21} cm^{-3} and an electron temperature of 50 eV.[2] A driving pulse with a duration of only 50 fs is required at this density to keep stimulated Raman scattering from heating the plasma above 50 eV.

III. Kinetic Issues for Lasing to Ground State

The efficiencies calculated for the $3d_{5/2} - 2p_{3/2}$ transition in Li-like Ne use a shell-averaged atomic physics model. The populations of the sublevels, in a given shell corresponding to a principle quantum number, are assumed to be proportional to the statistical weights of each sublevel. We discuss two issues that can affect the validity of this approximation for the $n = 2$ levels in Li-like Ne. (These issues also affect the $n = 3$ sublevels but to a lesser amount.) The first arises when the energy differences between the sublevels is not much less than the electron temperature. The second occurs when a given fine-structure transition becomes saturated and a large fraction of the population flow between shells is carried by that transition. We study these issues by comparing shell-averaged results with those obtained using a detailed atomic model that allows independent sublevels.

The assumption that the sublevels are populated according to their statistical weights assumes that $\Delta E_{max} \ll kT_e$, where E_{max} is the maximum energy difference between any of the sublevels. In the collisional limit, the ratio of populations is $n_j/n_i = (g_j/g_i)\exp(-\Delta E_{ij}/kT_e)$. The $2p_{3/2}$ and $2p_{1/2}$ levels have energies approximately 16 eV greater than the $2s$ level giving a Boltzmann factor $e^{-\Delta E/kT}$ between the $2p$ levels and the $2s$ level of 0.7 for a representative temperature from Fig. 1 of 40 eV. The $n = 2$ shell is primarily populated by radiative transitions into the $2p$ sublevels from the $3d$ sublevels. The $2s$ sublevel is populated radiatively from the $3p$ sublevels and collisionally from the $2p$ sublevels. These $\Delta n = 0$ collisions try to keep a Boltzmann population distribution among the sublevels. The electron collision rate between $2p_{3/2}$ and $2s$ is approximately a factor of 2 larger than that between $2p_{1/2}$ and $2s$. Ion collisions are included in our calculations but do not play an important role. The result of all these processes is that at the time of maximum gain the $2p_{3/2}$ level is slightly underpopulated compared with the other $n = 2$ levels accounting for statistical weights but not as much as predicted by the Boltzman factor. The effect of this on gains is shown in Fig. 2 where gains for three fine-structure transitions are shown for an electron density of 2.5×10^{20} cm^{-3} and an electron temperature of 40 eV. The solid curves are for independent sublevels and the dashed curves are the gains if the sublevels are populated according to their statistical weights. The $3d_{5/2} - 2p_{3/2}$ transition has a slightly higher gain when sublevels are treated independently primarily because of the reduced $2p_{3/2}$ population giving a larger inversion ratio.

Saturation by the $3d_{5/2} - 2p_{3/2}$ transition selectively populates the $2p_{3/2}$ level because a large fraction of the population flow between the $n = 3$ and $n = 2$ levels to pass through this transition. We find that the saturated gain using independent sublevels is often slightly smaller than the saturated gain obtained by assuming levels are populated statistically. Thus the two effects we describe act in different directions on the $2p_{3/2}$ sublevel. The general conclusion is that the assumption of statistical population between the sublevels is appropriate.

IV. Summary

We have shown the importance of including the lower laser level in calculations of saturation when that level is the ground state of an ion. We have calculated efficiencies of 10^{-5} to 10^{-4} for the $3d_{5/2} - 2p_{3/2}$ transition at 98 Å in Li-like Ne. The assumption that the fine-structure levels are populated according to their statistical weights is shown to be justified.

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