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XUV and soft X-ray laser radiation from nickel-like lanthanide

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Atomic structure data and effective collision strengths for $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^{10}$ and 54 fine-structure levels contained in the configurations $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^9\,4l$ ($l = s, p, d, f$) for the nickel-like La ion have been investigated. These data are used in the determination of the reduced population for the 55 fine structure levels over a wide range of electron densities (from 10^{20} to 10^{22}) and at various electron plasma temperatures. The gain coefficients for those transitions with positive population inversion factor are determined and plotted against the electron density.

Keywords: XUV, soft X-ray, laser radiation, population inversion, gain coefficient.

1. Introduction

Nickel-like ions are of considerable interest in laser-plasma interaction because of the large gain in the EUV and X-ray regions. Their ground state ($1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^{10}\,{}^1S_0$) is analogous to the ($1s^2\,2s^2\,2p^6\,{}^1S_0$) ground state of neon-like ions, which have already shown significant amplification in a number of elements such as selenium, germanium, and titanium. Similar laser gain has been predicted and observed by Goldstein *et al*. [1] in a number of nickel-like ions, including tin, neodymium, samarium, gadolinium, europium, tantalum, and tungsten.

Theoretical calculations were needed to approve these observations. Several calculations [1–4] have appeared in the literature for the nickel-like ions, reporting the atomic data for energy levels, radiative rates, collision strengths, and excitation rate coefficients to predict significant amplification. But not much work has been done to predict the laser gain of Ni-like ions theoretically. In this paper, we present the gain predicted for the Ni-like La ion by a steady-state model, the present model treats the kinetics of the Ni-like charge state in isolation from other ionization stages. The present gain calculations have included the ground state $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^{10}$ and 54 fine-structure levels contained in the configurations $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^9\,4l$

($l = s, p, d, f$) for the nickel-like La ion. The model includes all radiative transitions as well as electron-impact transitions between all levels.

2. Computation of gain coefficient

The possibility of laser emission from plasma of La^{29+} ion via electron collisional pumping, in the XUV and soft X-ray spectral regions is investigated at different plasma temperatures and plasma electron densities.

The reduced population densities are calculated by solving the coupled rate equations [5–8]

$$N_j \left[\sum_{i<j} A_{ji} + N_e \left(\sum_{i<j} C_{ji}^d + \sum_{i>j} C_{ji}^e \right) \right] = N_e \left(\sum_{i<j} N_i C_{ij}^e + \sum_{i>j} N_i C_{ij}^d \right) + \sum_{i>j} N_i A_{ij} \tag{1}$$

where N_j is the population of level j, A_{ji} is the spontaneous decay rate from level j to level i, C_{ji}^e is the electron collisional excitation rate coefficient, and C_{ji}^d is the electron collisional deexcitation rate coefficient, which is related to electron collisional excitation rate coefficient by [9, 10]

$$C_{ji}^d = C_{ij}^e \left[\frac{g_i}{g_j} \right] \exp\left(\frac{\Delta E_{ji}}{KT_e} \right) \tag{2}$$

where g_i and g_j are the statistical weights of lower and upper levels, respectively.

The electron impact excitation rates are usually expressed via the effective collision strengths γ_{ij} as

$$C_{ij}^e = \frac{8.6287 \times 10^{-6}}{g_i T_e^{1/2}} \gamma_{ij} \exp\left(\frac{E_{ij}}{KT_e} \right) \quad \left[\mathrm{cm^3 s^{-1}} \right] \tag{3}$$

The values of γ_{ij} and A_{ji} are taken from [1].

The actual population density N_J of the j-th level is obtained from the following identity [1],

$$N_J = N_j \times N_I \tag{4}$$

where N_I is the quantity of ions which reach to ionization stage I, being given by

$$N_I = f_I \frac{N_e}{Z_{\mathrm{av}}} \tag{5}$$

where f_I is the fractional abundance of the Ni-like ionization stages calculated by GOLDSTEIN *et al.* [1], N_e is the electron density, and Z_{av} is the average degree of ionization.

Since the populations calculated from Eq. (1) are normalized such that

$$\sum_{J=1}^{55}\left(\frac{N_J}{N_I}\right) = 1 \tag{6}$$

where 55 is the number of all the levels of the ion under consideration, the quantity actually obtained from Eq. (1) is the fractional population N_j/N_I.

After calculating level populations, the quantities N_u/g_u and N_l/g_l can be calculated.

Applying the electron collisional pumping, the collision in the lasant ion plasma will transfer the pumped quanta to other levels, and will result in population inversions between the upper and lower levels. Once the population inversion has been ensured a positive gain through $F > 0$ [11] is obtained

$$F = \frac{g_u}{N_u}\left[\frac{N_u}{g_u} - \frac{N_l}{g_l}\right] \tag{7}$$

where N_u/g_u and N_l/g_l are the reduced populations of the upper level and lower level, respectively. Equation (7) has been used to calculate the gain coefficient α for Doppler broadening of the various transitions in the La^{29+} ion,

$$\alpha = \frac{\lambda_{lu}^3}{8\pi}\left(\frac{M}{2\pi K T_i}\right)^{1/2} A_{ul} N_u F \tag{8}$$

where M is the ion mass, λ_{lu} is the transition wavelength in cm, T_i is the ion temperature in K and u, l represent the upper and lower transition levels, respectively.

As seen from Eq. (8), the gain coefficient is expressed in terms of the upper state density (N_u). This quantity, N_u, depends on how the upper state is populated, as well as on the density of the initial source state. The source state is often the ground state for the particular ion.

3. Results and discussion

3.1. Level population

The reduced population densities are calculated for 55 fine structure levels arising from $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^{10}$ and 54 fine-structure levels contained in the configurations $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^9\,4l$ ($l = s, p, d, f$) configurations using atomic data from literature [12]. The calculations have been done for the configurations that emit radiation in the XUV and soft X-ray spectral regions. The calculations were performed by solving the coupled rate Eq. (1) using simultaneously MATLAB version 7.3.0 computer program.

The present calculations for the reduced populations as a function of electron densities are plotted in Figures 1**a** through 1**b** at three different plasma temperatures (800, 1000, 1500 eV) for La^{29+} ion. In the calculation we took into account spontaneous

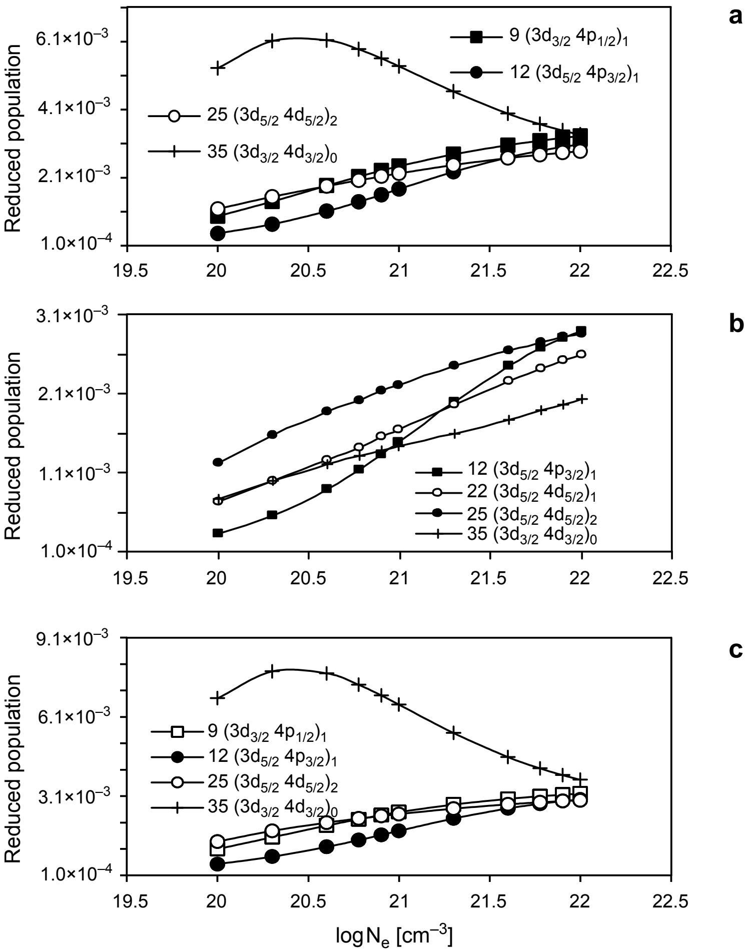

Fig. 1. Reduced population of La^{29+} levels after electron collisional pumping as a function of the electron density at a temperature of 800 eV (**a**), 1000 eV (**b**), and 1500 eV (**c**).

radiative decay rate and electron collisional processes between all the levels under study.

The behavior of level populations of the various ions can be explained as follows: in general, at low electron densities the reduced population density is proportional to the electron density, where excitation to an excited state is followed immediately by radiative decay, and collisional mixing of excited levels can be ignored.

This result is in agreement with that of FELDMAN *et al.* [7, 8, 13]. See also the data for nickel-like Sm, W, and Eu [14–16]. At high electron densities ($N_e > 10^{22}$), the radiative decay to all the levels will be negligible compared to collisional depopulations and all the level populations become independent of the electron density and are approximately equal (see Fig. 1). The $(3d_{3/2}\ 4d_{3/2})_0$ level shows a peak at electron density $4{\times}10^{20}$ cm^{-3} before the other levels then decrease to the saturation faster than the other levels, which means that the nonradiative transitions dominate the deexcitation because of its higher energy and fast decay time. The population inversion is largest where electron collisional deexcitation rate for the upper level is comparable to radiative decay rate for this level [7, 13].

3.2. Radiative lifetime

The lifetimes are determined almost entirely from the allowed and the strong intercombination transitions. The radiative lifetime τ_u of an excited atomic state u is related to the atomic transition probability $A(u, l)$ by:

$$\tau_u = \frac{1}{\sum_l A_{ul}} \tag{9}$$

where the sum is extended over all the lower states which can be reached from the upper state by radiative decay.

Table 1 contains the present results of radiative lifetime for the upper and lower laser levels for the nickel-like La.

Table 1. Radiative lifetime for La^{29+} laser levels.

Index	Level	Life time [ns]
9	$(3d_{3/2}\,4p_{1/2})_1$	1.15×10^{-3}
12	$(3d_{5/2}\,4p_{3/2})_1$	3.01×10^{-4}
22	$(3d_{5/2}\,4d_{5/2})_1$	7.25×10^{-3}
25	$(3d_{5/2}\,4d_{5/2})_2$	6.72×10^{-3}
35	$(3d_{3/2}\,4d_{3/2})_0$	2.38×10^{-3}

The table shows that the lifetime ratio between the upper and lower laser levels 35/9 is 2, the ratio between 25/12 levels is 22, and the ratio between 35/12 is 8. The present calculations predict that the lifetime of the upper laser level must be longer than the lifetime of lower one to ensure the fast depletion of the population of lower level which helps the laser to sustain continuous or quasi-continuous wave operation.

3.3. Inversion factor

The reduced populations obtained in Section 3.1 are very important for gain calculations. In order to work in the XUV and X-ray spectral regions, we have chosen transitions between any two levels producing photons with wavelengths between 30 and 150 Å.

The population inversion is largest where the electron collisional deexcitation rate for the upper level is comparable to the radiative decay rate for this level. For example, the population inversion factor for the 35 → 9 transition at $N_e = 10^{21}$ cm^{-3} is equal to 0.72 at 1500 eV for La^{29+}.

3.4. Gain coefficient

As a result of population inversion there will be positive gain in laser medium. Equation (8) has been used to calculate gain coefficient for the Doppler broadening of various transitions in the La^{29+} ion. Our results for the maximum gain coefficient in cm^{-1} for those transitions having a positive inversion factor $F > 0$ in the case of La^{29+} are presented in Fig. 2.

The figures show that the population inversions occur for several transitions in the La^{29+} ion, however, the largest gain occurs for La^{29+} ion in $(3d_{3/2}\ 4d_{3/2})_0 \to \to (3d_{5/2}\ 4p_{3/2})_1$ $(35 \to 12)$ transition at a wavelength of 87.3 Å and electron temperatures of 800 and 1500 eV, but occurs in $(3d_{5/2}\ 4d_{5/2})_2 \to (3d_{5/2}\ 4p_{3/2})_1$ $(25 \to 12)$ transition at a wavelength of 123.34 Å and electron temperature of 1000 eV.

For Ni-like ions, the population inversion is due to strong monopole excitation from the $3d^{10}$ ground state to the $3d^9 4d$ configuration and also the radiative decay of

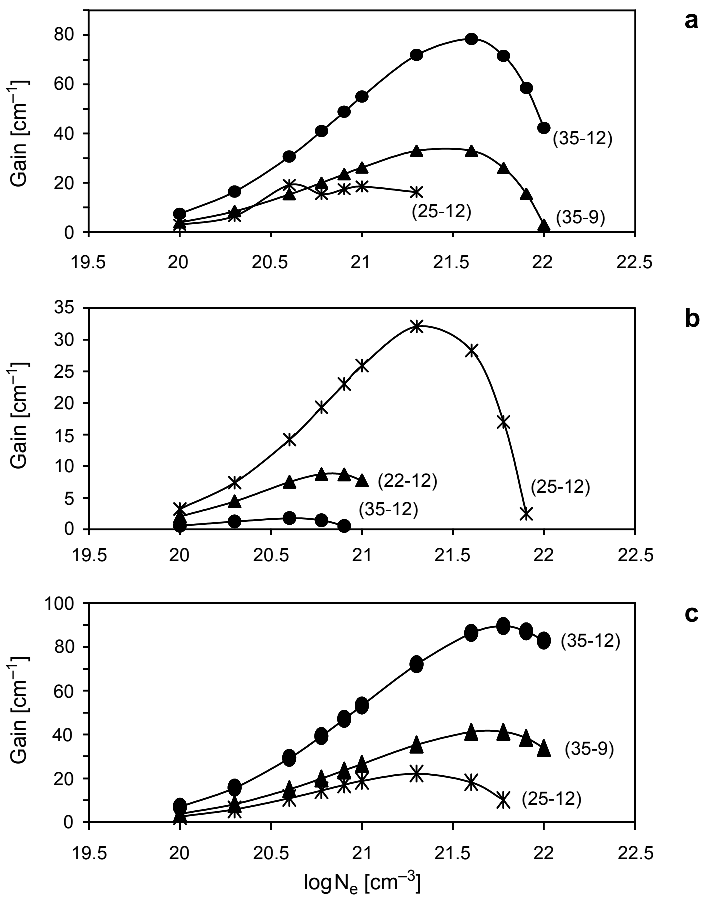

Fig. 2. Gain coefficient of possible laser transitions against electron density at a temperature of 800 eV (**a**), 1000 eV (**b**), and 1500 eV (**c**) in La^{29+}.

Table 2. Parameters of the most intense laser transitions.

Transition	Wavelength λ [Å]	Maximum gain α [cm^{-1}]	Electron density N_e [cm^{-3}]	Electron temperature T_e [eV]
$(3d_{3/2}\,4d_{3/2})_0 \rightarrow$ $\rightarrow (3d_{3/2}\,4p_{1/2})_1$	82.95	41.2	4×10^{21}	1500
$(3d_{5/2}\,4d_{5/2})_1 \rightarrow$ $\rightarrow (3d_{5/2}\,4p_{3/2})_1$	127.3	8.75	6×10^{20}	1000
$(3d_{5/2}\,4d_{5/2})_2 \rightarrow$ $\rightarrow (3d_{5/2}\,4p_{3/2})_1$	123.34	32.1	2×10^{21}	1000
$(3d_{3/2}\,4d_{3/2})_0 \rightarrow$ $\rightarrow (3d_{5/2}\,4p_{3/2})_1$	87.3	89.5	6×10^{21}	1500

the $3d^9 4d$ level to the ground level is forbidden, while the $3d^9 4p$ level decays very rapidly to the ground level.

These short wavelength laser transitions were produced using plasmas created by optical lasers as the lasing medium.

For electron densities and electron temperatures that are typical of laboratory high-density plasma sources, such as laser produced plasmas, it is possible to create a quasistationary population inversion between the $3d^9 4d$ and $3d^9 4p$ in La^{29+} ion. Our calculations have shown that under favorable conditions large laser gains for this transition in the XUV and soft X-ray regions of the spectrum can be achieved in the nickel-like La ion. It is obvious that the gain increases with temperature. These results are in agreement with Zhong *et al*. [12] expectation of laser gain at 8.8 nm of in La^{29+} ion.

4. Conclusions

The analysis presented in this work shows that electron collisional pumping (ECP) is suitable for attaining population inversion and offering the potential for laser emission in the spectral region between 50 and 150 Å from La^{29+} ion. This class of lasers can be achieved under suitable conditions of pumping power and electron density. If the positive gains obtained previously for some transitions in the ion under studies (La^{29+} ion) together with the calculated parameters could be achieved experimentally, then successful low-cost electron collisional pumping XUV and soft X-ray lasers can be developed for various applications. The parameters of most intense laser transitions in Ni-like La ion are summarized in Tab. 2.

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