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XUV and Soft X-Ray Laser Radiation from Ni-Like Au

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Abstract

Atomic structure data and effective collision strengths from literature for $1s^2\,2s^2\,2p^6\,3s^2\,3p^6 3d^{10}$ and 34 fine-structure levels contained in the configurations $1s^2\,2s^2\,2p^6\,3s^2\,3p^6 3d^9\,4l$ ($l = s, p, d$) for the nickel-like Au ion are used in the determination of the reduced population for these levels over a wide range of electron densities and at various electron plasma temperatures. The gain coefficient for those transitions with positive population inversion factor are determined and plotted against the electron density.

Keywords: Atomic Structure Data, Effective Collision Strengths, Reduced Population, Ni-Like Au

1. Introduction

Experimentally there exist in the literature some studies trying to develop high-efficiency X-ray laser with significant gain. For example Vinogradov *et al*. and Norton *et al.* [1,2] proposed the original mechanism for demonstrating X-ray lasing by resonant photopumping. Several authors during the past three decades [3-8] have studied this lasing mechanism experimentally and theoretically, in the hope of developing high-efficiency X-ray laser.

In another study by N. Qi and M. Krishnan [9], the shortest wavelength at which the significant gain has been measured using the resonant photopumping was in the beryllium-like carbon at 2163 Å, which is far from the X-ray spectral region.

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.* [10] in a number of nickel-like ions, including tin, neodymium, samarium, gadolinium, europium, tantalum, and tungsten.

Theoretical calculations are needed to approve these observations. Recently, Zeng *et al.* [11] calculated the energy levels, the spontaneous radiative decay rates, and the electron impact collisional strengths for Ni-like Gold ion. But no much work has been done to predict the laser gain of Ni-like Au theoretically. In this paper, we present the gain predicted for the Ni-like Au ion by a steady-state model of Ni-like ions, our model treats the kinetic of the Ni-like charge state in isolation from other ionization stages. The present gain calculations included the ground state $1s^2\,2s^2\,2p^6\,3s^2\,3p^6 3d^{10}$ and 34 fine-structure levels contained in the configurations $1s^2\,2s^2\,2p^6\,3s^2\,3p^6 3d^9\,4l$ ($l = s, p, d$) for the nickel-like Au 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 Au^{51+} 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 [12-15].

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

where N_j is the 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 de-excitation rate coefficient, which is related to electron collisional excitation rate coefficient by [16,17].

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

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

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

$$C_{ij}^{e} = \frac{8.6287\times10^{-6}}{g_i T_e^{1/2}}\gamma_{ij}\exp\frac{E_{ij}}{KT_e}\ \mathrm{cm}^3\cdot\mathrm{sec}^{-1} \tag{3}$$

where the values of γ_{ij} and A_{ji} are obtained by [11].

The actual population density N_J of the j^{th} level is obtained from the following identity [10],

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

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

$$N_I = f_I\, N_e / Z_{avg} \tag{5}$$

where f_I is the fractional abundance of the Ni-like ionization stages calculated by Goldstein *et al.* [10], N_e is the electron density, and Z_{avg} is the average degree of ionization

Since the populations calculated from Equation (1) are normalized such that,

$$\sum\nolimits_{J=1}^{35}\left(\frac{N_J}{N_I}\right) = 1 \tag{6}$$

where 35 is the number of all the levels of the ion under consideration, the quantity actually obtained from Equation (1) is the fractional population N_j/N_I .

After the calculation of levels population, the quantities $N_u/g_u$and N_l/g_l can be calculated.

By application of 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 a population inversion has been ensured a positive gain through $F > 0$ [18] is obtained.

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

where $\frac{N_u}{g_u}$ and $\frac{N_l}{g_l}$ 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 Au^{51+} ion.

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

where M is the ion mass, $\lambda_{\ell u}$ 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 Equation (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. Result and Discussions

3.1. Level Population

The reduced population densities are calculated for 35 fine structure levels arising from $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6 3d^{10}$ and 34 fine-structure levels contained in the configurations $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6 3d^9\ 4l$ ($l = s, p, d$) configurations that emit radiation in the XUV and soft X-ray spectral regions. The calculations were performed by solving the coupled rate Equation (1) simultaneously using MATLAB version 7.8.0 (2009a) computer program.

The present calculations for the reduced populations as a function of electron densities are plotted in **Figures 1-3** at three different plasma temperatures (0.5, 1, 1.5 KeV) for Au^{51+} ion.

In the calculation we took into account spontaneous radiative decay rate and electron collisional processes between all levels under study.

The atomic structure data and effective collision strength data needed were taken from Reference [11].

The behavior of level populations 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.* [14,15,19]. See also the data for nickel-like Sm , W, and Eu [20-22].At high electron densities ($N_e > 10^{23}$), 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 (see **Figures 1-3**). The $(3d_{3/2}\ 4d_{3/2})_0$ level has higher population density from electron density 10^{21} to 10^{22} cm^{-3} than the other levels at electron temperature 0.5 KeV, from electron density 10^{21} to 2 × 10^{22} cm^{-3} at electron temperature 1 KeV, and from electron density 10^{21} to 4 × 10^{22} cm^{-3} at electron temperature 1.5 KeV which mean

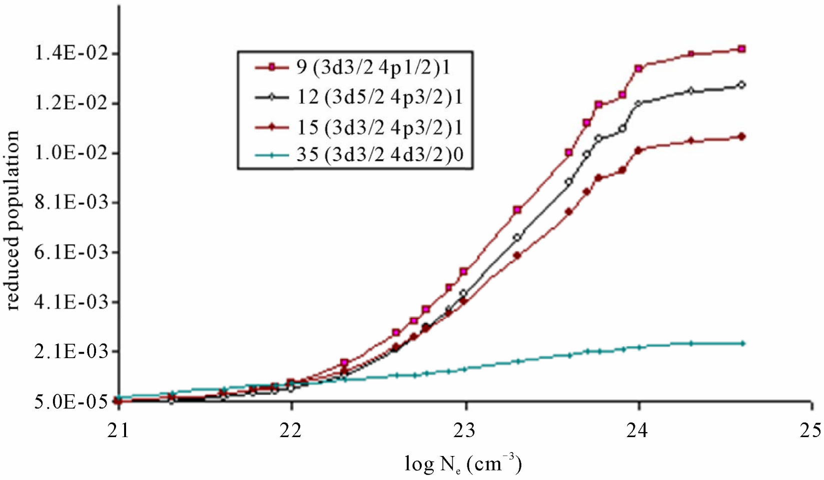

Figure 1. Reduced population of Au^{51+} levels after electron collisional pumping as a function of the electron density at temperature 0.5 KeV.

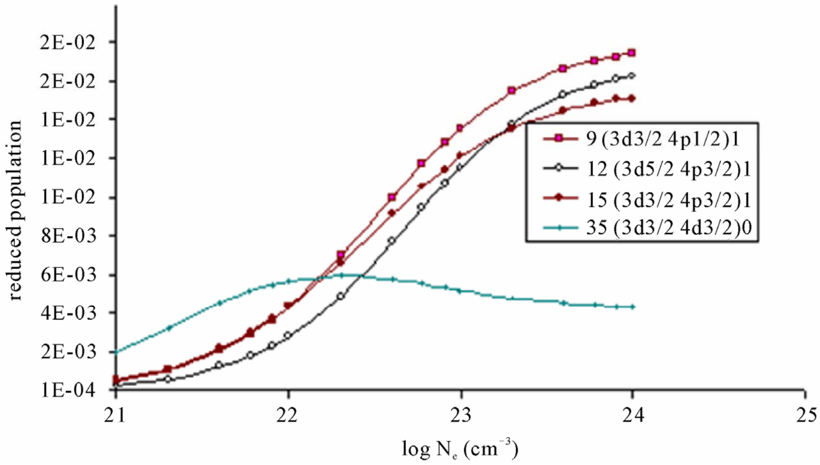

Figure 2. Reduced population of Au^{51+} levels after electron collisional pumping as a function of the electron density at temperature 1.0 KeV.

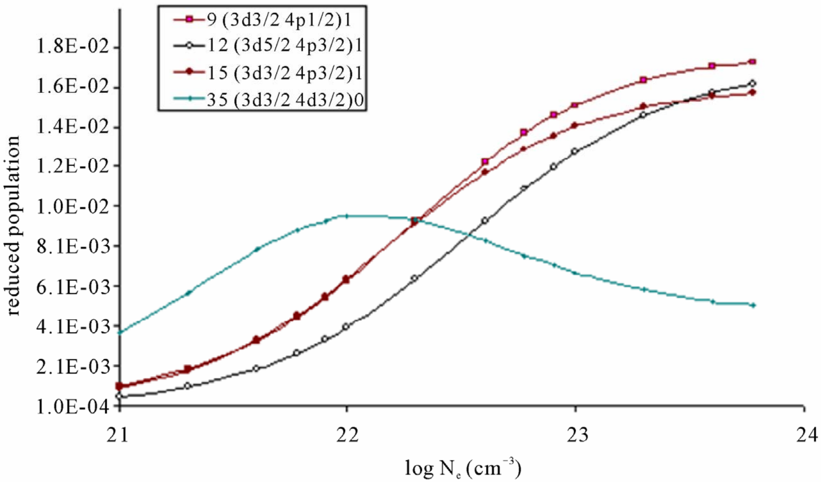

Figure 3. Reduced population of Au^{51+} levels after electron collisional pumping as a function of the electron density at temperature 1.5 KeV.

that the population inversion occur in these ranges. 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 [14,19]. The difference between this work and our previous work on Gd-like nickel [23] we took into account the $n = 4$ shell, however in the case of Au-like nickel we took $n = 3$ shell only to decrease the time and complexity of calculations because we did not find any significant laser transitions come from $3d^9$ $4f$ - $3d^9$ $4d$ transitions and all laser transitions mainly from $3d^9$ $4d$ - $3d^9$ $4p$. The population inversion in case of Au-like nickel is at higher electron density than the in the case of Gd-like nickel.

3.2. 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 Au^{51+} 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 Au^{51+}, in **Figures 4-6**.

The figures show that the population inversions occur for several transitions in the Au^{51+} ion, however, the largest gain occurs in $(3d_{3/2}\ 4d_{3/2})_0 \rightarrow (3d_{5/2}\ 4p_{3/2})_1$ (35→12) transition at wavelength 41.4 Å at an electron

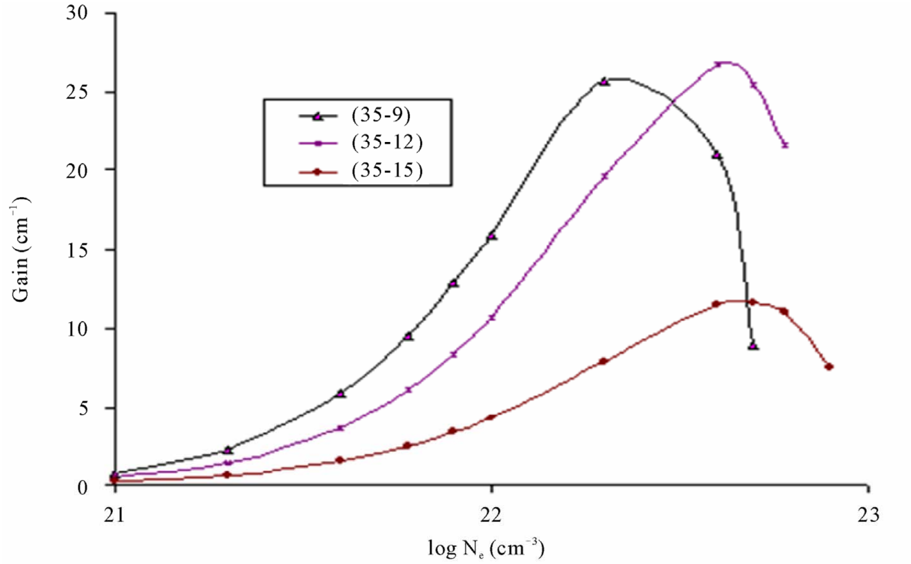

Figure 4. Gain coefficient of possible laser transitions against electron density at temperature 0.5 KeV in Au^{51+}.

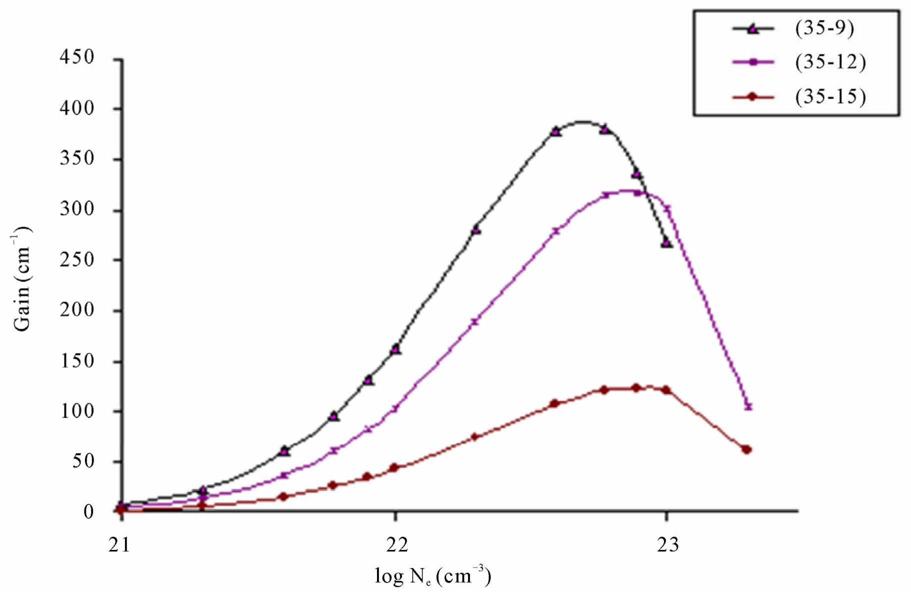

Figure 5. Gain coefficient of possible laser transitions against electron density at temperature 1.0 KeV in Au^{51+}.

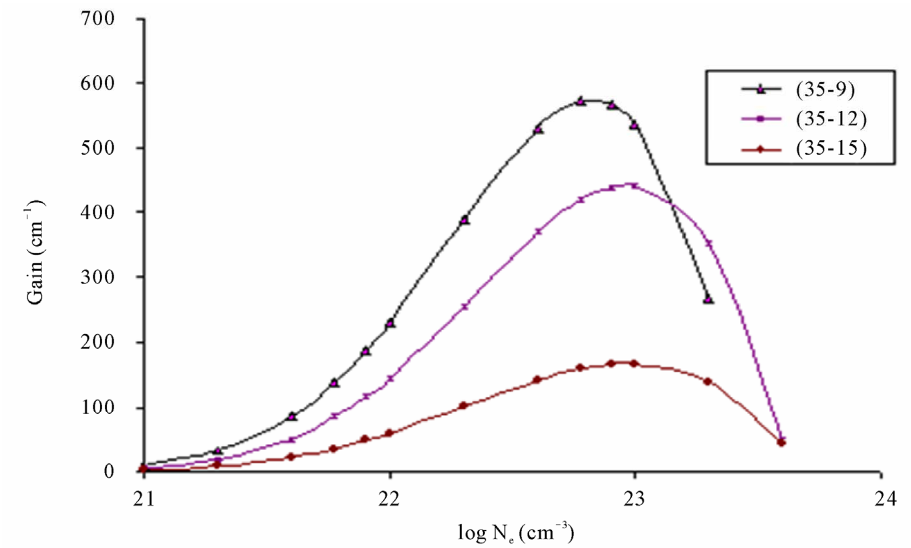

Figure 6. Gain coefficient of possible laser transitions against electron density at temperature 1.5 KeV in Au^{51+}.

Table 1. Parameters of the most intense laser transitions.

Transition	Atomic data	Au XXXXXII
$(3d_{3/2}4d_{3/2})_0 \rightarrow (3d_{3/2}4p_{1/2})_1$	Wavelength λ (Å)	35.1
	Maximum gain α (cm^{-1})	572
	Electron density N_e (cm^{-3})	6.00E+22
	Electron temperature T_e (KeV)	1.5
$(3d_{3/2}4d_{3/2})_0 \rightarrow (3d_{5/2}4p_{3/2})_1$	Wavelength λ (Å)	41.4
	Maximum gain α (cm^{-1})	442
	Electron density N_e (cm^{-3})	1.00E+23
	Electron temperature T_e (KeV)	1.5
$(3d_{3/2}4d_{3/2})_0 \rightarrow (3d_{3/2}4p_{3/2})_1$	Wavelength λ (Å)	51
	Maximum gain α (cm^{-1})	166
	Electron density N_e (cm^{-3})	8.00E+22
	Electron temperature T_e (KeV)	1.5

temperature 0.5 KeV, and in $(3d_{3/2}\ 4d_{3/2})_0 \rightarrow (3d_{3/2}\ 4p_{1/2})_1$ (35→9) transition at wavelength 35.1 Å at an electron temperatures 1.0, and 1.5 KeV

For Ni-like Au, 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 the $3d^9\ 4d$ level to the ground level is forbidden, while the $3d^9\ 4p$ level decays very rapidly to the ground level.

This short wavelength laser transitions was 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 quasi-stationary population inversion between the $3d^9 4d$ and $3d^9 4p$ in Au^{51+} ion. Our calculations have shown that under favorable conditions large laser gain for these transitions in the XUV and soft X-ray regions of the spectrum can be achieved in the nickel like Au^{51+} ion. It is obvious that the gain increases with the temperature.

4. Conclusions

The analysis that have been 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 30 and 100 Å from Au^{51+} ion. This class of lasers can be achieved under suitable conditions of pumping power as well as electron density. If the positive gain obtained previously for some transitions in the ion under studies (Au^{51+} 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 Au ion are summarized in **Table 1**.

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