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Search for Laser Lines in Sodium-Like Fe Plasmas

Wessameldin S. Abdelaziz[1], Mai E. Ahmed[2], Tharwat M. El-Sherbini[3], Mohammed Alshaik Ahmed[4], Ali S. Khalil[5]
[1]National Institute of Laser Enhanced Seiences, Cairo University, Giza, Egypt
[2]Environmental Affairs Agency, Cairo, Egypt
[3]Laboratory of Lasers and New Materials, Cairo University, Giza, Egypt
[4]Al-Azhar University in Palastine, Ghaza, Palastine
[5]Tebin Institute for Metrological Studies (TIMS), Cairo, Egypt
Email: wessamlaser@yahoo.com

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ABSTRACT

Energy levels, transition probabilities and effective collision strength for $1s^2\ 2s^2\ 2p^6\ 3l,\ 4l,\ 5l$ ($l = 0, 1, 2, 3, 4$) states of sodium-like Fe are used in the determination of the reduced populations for 21 fine structure levels over a wide rang of electron density values (10^{18} to $10^{20}\ cm^{-3}$) and at against electron plasma temperatures. Gain coefficients are evaluated and plotted against the electron density.

Keywords: XUV; Soft X-Ray; Laser Emission; Gain Coefficient

1. Introduction

Emission lines arising from transitions in ions of the sodium iso-electronic sequence can be among the strongest observed ones in the solar ultraviolet spectrum [1]. The line ratios involving Na-like iron transitions are potentially very useful for electron temperature (T_e) diagnostics of the solar transition region [2], and it is noted that Na-like ions may be employed as abundance indicators [3]. Moreover, it has been shown that Na-like ion emission-line ratios provide electron density (N_e) diagnostics for high-density laboratory plasmas, such as tokomaks [4].

Over the last decade recombination and resonantly photopumped X-ray laser schemes on the n = 3 – 6 to n' = 2 – 4, the lasing transitions in H, He, Li and Na-like ions were extensively studied both experimentally and theoretically [5].

The modeling of laboratory X-ray lasers is routinely based on the calculations of the gain coefficients (G) involved laser levels [5]. In these calculations of the populations of the upper and lower laser levels are given from the kinetics data and the peak values of spectral functions for the potential lasing transitions.

For recombination and resonantly photopumped X-ray laser schemes, however, the strongest laser lines are usually found in the long-wavelength part of the n to n' emission spectra represented by a number of closely-spaced or even overlapping lines that may be strongly affected by the ion Stark broadening. In addition, theoretical studies of particular X-ray laser schemes using CR models have shown that these lines often correspond to transitions with different values of population inversion [5,6].

The purpose of this work is to use the atomic data to calculate reduced populations of sodium-like Fe excited levels over a wide range of electron densities and at various electron temperatures. The gain coefficients are also calculated. In order to search for laser lines in sodium-like Fe plasma, these data might help experimentalists in developing soft X-ray lasers.

2. Computation of Gain Coefficient

The possibility of laser emission from plasma of ions of Fe 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 [7-10].

$$N_j\left[\sum_{i<j} A_{ji} + N_e\left(\sum_{i<j} C^d_{ji} + \sum_{i>j} C^e_{ji}\right)\right] = N_e\left(\sum_{i<j} N_i C^e_{ij} + \sum_{i>j} N_i C^d_{ij}\right) + \sum_{i>j} N_i A_{ij} \quad (1)$$

where N_j is the the population of level j, A_{ji} is the spontaneous decay rate from level j to level i, C^e_{ji} is the electron collisional excitation rate coefficient, and C^d_{ji} is the electron collisional de-excitation rate coefficient, which is related to electron collisional excitation rate coefficient by [11,12].

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

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

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

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

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

$$N_J = N_j \times N_I \quad (4)$$

where N_I is the quantity of ions which reach the ionization stage I and is given by [13]

$$N_I = f_I\, N_e/Z_{avg} \quad (5)$$

where f_I is the fractional abundance of the Ni-like ionization stages calculated by Goldstein *et al.* [13], N_e is the electron density, and Z_{avg} is the average degree of ionization.

Since the populations calculated from Equation (7) are normalized such that

$$\sum_{J=1}^{21}\left(\frac{N_J}{N_I}\right) = 1 \quad (6)$$

where 21 is the number of all the levels of the ion under consideration.

Electron collisional pumping has been applied. Collision in the lasant ion plasma will transfer the pumped quanta to other levels, and may lead to population inversions between the upper and lower levels.

Once a population inversion has been ensured, a positive gain whith result F > 0 [14].

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

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 (11) has been used to calculate the gain coefficient for Doppler broadening of the various transitions in the Na-like Fe ion, [14].

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

where M is the ion mass, $\lambda_{\ell u}$ is the transition wavelength in cm, T_i is the ion temperature in $0K$ and u, l represent the upper and lower transition levels respectively.

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

3. Results and Discussions

3.1. Level Populations

The reduced population densities are calculated for 21 levels by solving the coupled rate Equations [14], and plotted for 21 levels using atomic data from literature [15]. The gain was calculated using Matlab version 7.3.0 computer program for solving simultaneous coupled rate equations.

Our calculations for the reduced populations as a function of electron densities are plotted in **Figure 1** at one plasma temperatures (3/4 of the ionization potential) for Na-like Fe.

We took into account in the calculation spontaneous radiative decay rate and electron collisional processes between all 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 radiation decay, and collisional mixing of excited levels can be ignored.

We expect that at high densities ($N_e > 10^{20}$ cm^{-3}), radiative decay to all levels will be negligible compared to collisional depopulations and all level population become independent of electron density and are approximately the same (see ref. [16-18]). The population inversion is largest when electron collisional de-excitation rate for the upper level is comparable to the radiative decay of this level [10].

From our study, it was found that the gain coefficient was very low at 1/4 and 1/2 ionization potentials for all elements, and therefore the obtained gain coefficient and reduced population have not been included in **Figure 2**.

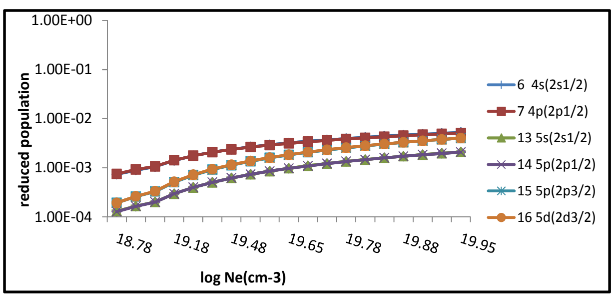

Figure 1. Reduced population of Fe^{15+} levels after electron collisional pumping as a function of the electron density at temperature 367 eV.

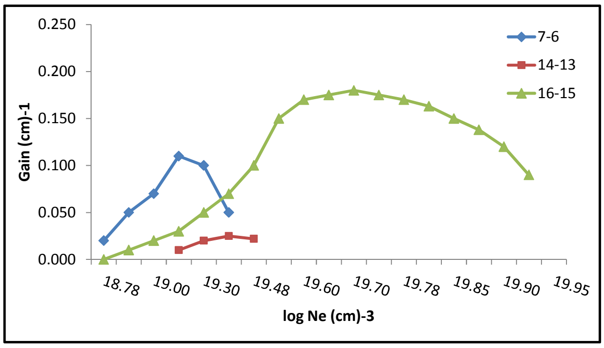

Figure 2. Gain coefficient of possible laser transitions against electron density at temperature 367 eV in Fe^{15+}.

3.2. Inversion Factor

As we mentioned before, laser amplification will occur only if there is population inversion or in other words for positive inversion factor $F > 0$. In order to work in the XUV and soft X-ray spectral regions, we have chosen transitions between any two levels producing photons with wavelength between 30 and 1000 Å. The electron density at which the population reaches collisional equilibrium approximately equal to A/D, where A is the radiative decay rate and D is the collisional de-excitation rate [9]. The population inversion is largest when the electron collisional de-excitation rate for the upper level is comparable to the radiative decay rate for this level.

For increasing atomic number Z, the population inversion occurs at higher electron densities, this is due to the increase in the radiative decay rate with Z and the decrease in collisional de-excitation rate coefficient with Z [19].

3.3. Gain Coefficient

As a result of population inversion there will be a positive gain in laser medium. Equation (8) has been used to calculate gain coefficient for the Doppler broadening of various transitions in the Na-like Fe.

Our results for the maximum gain coefficient in cm^{-1} of those transitions having a positive inversion factor $F > 0$ in the case of Fe^{15+} ion at different temperatures are calculated and plotted against electron density in **Figure 2**.

The figure shows that the population inversion occurs for several transitions in the Fe^{15+} ion, however the largest gain occurs for the Fe^{15+} ion at $5d(^2D_{3/2})\rightarrow 5p(^2P_{3/2})$ transition.

For Na-like Fe, the population inversion is due to a strong monopole excitation from the 3s ground state to the 3s 4d configuration and also the radiative decay of the 3s 4d level to the ground level is forbidden, while the 3s 4p level decays very rapidly to the ground level.

These short wavelength laser transitions were produced using plasmas as the lasing medium created by electron impact excitation.

Table 1. Parameters of the most intense laser transitions in Fe^{15+} ion plasma.

Transition	Atomic data	Fe XVI
$4p\ (^2p_{1/2})\rightarrow 4s\ (^2s_{1/2})$	Wavelength λ (Å)	904
	Maximum gain α (cm^{-1})	0.105
	Electron density N_e (cm^{-3})	1.50E+19
	Electron temperature T_e (eV)	367.02
$5p\ (^2p_{1/2})\rightarrow 5s\ (^2s_{1/2})$	Wavelength λ (Å)	835
	Maximum gain α (cm^{-1})	0.0218
	Electron density N_e (cm^{-3})	2.50E+19
	Electron temperature T_e (eV)	367.02
$5d\ (^2d_{3/2})\rightarrow 5p\ (^2p_{3/2})$	Wavelength λ (Å)	493
	Maximum gain α (cm^{-1})	2.00E−01
	Electron density N_e (cm^{-3})	6.00E+19
	Electron temperature T_e (eV)	367.02

4. Conclusion

The analysis that has 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 50 and 1000 Å from the Na-like Fe. This class of lasers can be achieved under the suitable conditions of pumping power as well as electron density. The positive gains obtained previously, for some transitions in the ion under study (Fe^{15+} ion) together with the calculated parameters could be achieved experimentally, then successful low cost electron collisional pumping XUV and soft X-ray lasers could be developed for various applications. The results suggested that some laser transitions in the Fe^{15+} plasma ions, as the most promising laser emission lines in the XUV and soft X-ray spectral regions (**Table 1**).

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