JP9955052

Theoretical Predictions for the Polarization of the J=0-1 Neonlike Germanium X-Ray Laser Line in the Presence of a Directed Beam of Hot Electrons

M. K. Inal
Institut de Physique, Université A. Belkaid, BP 119
13000 Tlemcen, Algeria

J. Dubau and M. Cornille
UPR-176 CNRS, DARC, Observatoire de Paris
92190 Meudon Cedex, France

Abstract

The polarization of the neonlike germanium $J = 0 - 1$ laser line, which would arise from the existence of a directed beam of hot electrons in the amplifying plasma, is theoretically investigated. The relative populations of the magnetic sublevels in the lower J=1 laser level have been determined by allowing for the processes of direct excitation from the $2p^6$ ground level and collisional de-excitation from the upper J=0 laser level. Elastic collisions leading to transitions between the $M_J = 0$ and $M_J = 1$ sublevels within the lower level of the lasing line have also been taken into account. The required elastic and inelastic collision strengths for transitions between magnetic sublevels have been computed in a semi-relativistic distorted-wave approximation, for incident electron energies up to 15 keV. Our calculations predict a rather low degree of polarization for the J=0 − 1 line, although the elastic collisions are found to play a negligibly small role in the redistribution of magnetic sublevel populations.

1. Introduction

Amplification properties of soft-x-ray $(1s^2 2s^2 2p^5)3p \rightarrow (...)3s$ lasing lines in high density plasmas containing Ne-like ions collisionally excited by electrons have been studied intensively both theoretically [1] and experimentally [2]. While predicted to have the highest gain, the $(...)3p\ ^1S_0 \rightarrow (...)3s\ ^3P_1$ (so called $J = 0 - 1$ line) was not significantly amplified in the first x-ray laser experiments [3] because of refraction resulting from the large electron density gradients. This line is pumped almost totally by the strong monopole collisional excitation from the $1s^2 2s^2 2p^6$ ground level. Its gain has been demonstrated to be the largest for most Ne-like ions at early times, and quickly becomes weaker than those of the two main $J = 2 - 1$ lines [4]. Important improvements in the performance of the $J = 0 - 1$ laser beam have been achieved by the use of prepulse [5] and multiple pulse [6] techniques which allow to create a larger and more uniform density plasma.

In a recent x-ray laser experiment involving germanium plasma created by two 0.1 ns pulses [7], the $J = 0 - 1$ line at 19.6 nm was found to be appreciably polarized along the target surface, with a degree of polarization of -0.53. Kawachi et al. [7] attributed the observed polarization to the difference in the gains between the "π" (parallel) and "σ" (perpendicular) components, arising from a nonuniform distribution of population densities among the magnetic sublevels $M_J = 0$ and $|M_J| = 1$ of the lower J=1 level. A ratio of about 3.5 between the populations of the $M_J = 0$ and $|M_J| = 1$ sublevels was required to explain the measured polarization degree. This selective M_J sublevel population was interpreted by the authors as due to the effect of anisotropy in the radiation trapping of photons of the 0.98 nm 3s $^3P_1 \rightarrow$ 2p^6 $^1S_0$ resonance line, in an expanding plasma which has a velocity gradient in the direction perpendicular to the target surface. In a very recent work [8], it has been shown that the effects of radiation trapping are quite negligible, and cannot explain the experimental result reported in ref. [7]. For the two main $J = 2 - 1$ lasing lines, which appear at 23.2 and 23.6 nm in Ge^{22+}, no polarization was observed [9].

The purpose of the present work is to investigate theoretically the polarization of the $J = 0 - 1$ Ge^{22+} lasing line that would result from the presence of a directed beam of hot electrons in the amplifying plasma. As it is well known, electron-ion collisional processes involving incident electrons with an anisotropic velocity distribution leads in general to preferential population of particular magnetic sublevels within an ionic level $J > 1/2$ [10]. Hot electrons with a highly anisotropic angular distribution could be generated in plasmas produced by irradiation of solid targets with high-intensity short- and ultrashort-duration (ps down to tens of fs) laser pulses [11]. Polarization of x-ray emission from this kind of plasmas was observed [12], and the measured polarization of the 1s2p $^1P_1$-1s^2 $^1S_0$ resonance line of He-like aluminum ions provided a very useful tool for probing the strong anisotropy of the electron angular distribution due to nonlocal heat transport.

2. Inelastic and elastic collision rates

The $J = 0$ upper level (denoted u level) of the lasing line is populated almost entirely by direct collisional excitation from the 2p^6 $^1S_0$ ground level (g level) and depopulated primarily through the spontaneous radiative decay and collisional de-excitation to the $J = 1$ lasing line lower level (l level) as well as the collisional excitation to the more highly excited level (...) 3d $^1P_1$. For the l level, three populating processes have been taken into consideration in the present study, namely the collisional excitation from the g level and the spontaneous radiative decay and collisional deexcitation from the u level. The depopulation of the l level has been assumed to occur by means of a strong spontaneous radiative transition to g and a collisional excitation to u. Also taken into account are the transitions between magnetic sublevels of l level caused by elastic electron-ion collisions. We will be concerned here with the plasma period when the $J = 0$ - 1 lasing line is unsaturated, so that stimulated emission can be ignored in the population equations. We have chosen a bi-Maxwellian electron distribution for the free electrons, i.e.

$$F(E,\theta) = (1-f)\frac{2}{\sqrt{\pi}(kT_1)^{3/2}}E^{1/2}e^{(-\frac{E}{kT_1})}\phi_1(\theta) + f\frac{2}{\sqrt{\pi}(kT_2)^{3/2}}E^{1/2}e^{(-\frac{E}{kT_2})}\phi_2(\theta) \qquad (1)$$

where f and T_2 are, respectively, the hot electron fraction and the hot temperature. The temperature T_1 is a few hundred eV whereas T_2 lies in the multi-keV range. $\phi_1(\theta)$ is an isotropic angular distribution and $\phi_2(\theta)$ is a beam-like angular distribution along the quantization axis z, corresponding to the direction of the "pump" laser (normal to the target surface). The excitation rate coefficient C for each collisional transition can be determined from the combination $(1 - f)\,C^{(1)}(T_1) + f\,C^{(2)}(T_2)$ of two Maxwellian-averaged rate coefficients. The elastic and inelastic collision strengths needed in evaluating the $C^{(i)}$ coefficients have been computed over a wide energy range in the distorted-wave approximation using the basic codes DISWA [13] and JAJOM [14]. For the dipole excitations $g \rightarrow l, M_J$ and $u \rightarrow l, M_J$ and de-excitations $l, M_J \rightarrow u$ at relatively large impact-electron energies, the Coulomb-Bethe method was also employed to calculate the important contribution from higher partial waves. In Tables Ia and Ib are given the calculated rate coefficients for collisional transitions caused by the two groups of electrons, over the temperature ranges 200-500 eV and 2-8 keV, respectively. The rate coefficients for the transitions between $M_J = 0$ and 1 magnetic sublevels induced by elastic collisions with the isotropic cold electrons are also presented in Table Ia. Note that the rate coefficient for $l \rightarrow u$ has not been included in Table Ia since it can be obtained from $C_d\,(u \rightarrow l)$ by using the principle of detailed balance. It can first be seen that the elastic collision rate coefficients are very small comparatively to $C_d\,(u \rightarrow l)$ and $C_e\,(l \rightarrow u)$. Therefore the effect of elastic collisions in the redistribution of populations among the magnetic sublevels of the lower laser level can be neglected. It can also be seen from Table Ib that for the directive electrons the excitation process from g level populates preferentially the $l, M_J = 0$ sublevel while the collisional de-excitation from u level favours the $|MJ| = 1$ sublevels. Our calculations predict that at, for example, an (electron-beam) impact energy of 250 Ry relative to the ground level, the cross-section ratios σ_0/σ_1 between the $M_J = 0$ and 1 sublevels are about 4.5 and 0.53, respectively, for excitation from g and deexcitation from u. It is worth mentioning that for the third process involved in the population of l level, i.e. the spontaneous radiative decay from u level, there is no selection with respect to the l magnetic sublevels.

3. Magnetic sublevel populations

The populations of the upper level and lower magnetic sublevels involved in the Ge^{22+} $J = 0 - 1$ lasing line were determined using the collisional rate coefficients listed in Tables Ia and Ib and the radiative transition probabilities computed with the SUPERSTRUCTURE code [15] and reported in Ref.[16]. The total electron density was fixed at 5x10^{20} cm^{-3} and the fraction of hot electrons was taken to be f =0.05 and f =0.1. Results of our calculations are presented in Table II for five selected values of the two electron temperatures T_1 and T_2. It appears that the largest ratio of the M_J =0 to M_J =1 populations occurs at low temperatures T_1 =200 - 300 eV. The M_J =0 sublevel is only slightly overpopulated with respect to M_J =1 when T_1 is greater than about 400 eV. Our calculations indicate that at, for example, T_1 =400 eV, T_2 =5 keV and f =0.05 about 75% of the population of the whole l level comes from collisional de-excitation from u level and 17% from excitation from g level. It should be mentioned that, in contrast to the excitation process from the 2p^6 level, the hot electrons are much less efficient in the collisional de-excitation of the u level because of the large difference between threshold energies for n =2 - 3 and n =3 - 3 transitions. This results in a weak preferential population of $l, M_J = 1$ sublevel by the collisional de-excitation process from u. For $f > 0.05$, the $g \rightarrow l$ excitation is due dominantly to hot electrons.

Conclusion

An analysis of the population processes of the sublevels of the lasing line $J = 0 - 1$ was presented. It was assumed the plasma to be in a steady state, the electron temperature and density corresponding to realistic values. The results show a very small possibility to have a strong polarization of the lasing line due to anisotropic electron excitation, except if the free electron are strongly anisotropic. One must not forget that a laser-produced plasma is far to be in a steady state situation, in particular when the X-ray lasing process starts. The atomic data presented here have therefore to be used in a time dependent collisional-radiative model. When the plasma parameters temporal gradients are large, the very different life times of the lower and upper level of the lasing line will become important.

Acknowledgements

One of us (MKI) gratefully acknowledges financial support of CNRS, France, during his three month stay in Meudon Observatory. He also would like to thank the Organizing Committee of ICPP 1996, Nagoya, Japan, for financial support allowing him to participate in the Conference during which the present work was initiated.

References

[1] P.B. Holden, S.B. Healy, M.T.M. Lightbody, G.J. Pert, J.A. Plowes, A.E. Kingston, E. Robertson, C.L.S. Lewis, and D. Neely, *J. Phys. B* **27**, 341 (1994).

[2] M. Murai, H. Shiraga, G. Yuan, H. Daido, H. Azuma, E. Miura, R. Kodama, M. Takagi, T. Kanabe, H. Takabe, Y. Kato, D. Neely, D.M. O'Neil, C.L.S. Lewis, and A. Djaoui, *J. Opt. Soc. Am. B* **11**, 2287 (1994).

[3] T.N. Lee, E.A. McLean, and R.C. Elton, *Phys. Rev. Lett.* **59**, 1185 (1987).

[4] D.M. O'Neil, C.L.S. Lewis, D. Neely, J. Uhomoibhi, M.H. Key, A.G. MacPhee, G.J. Tallents, S.A. Ramsden, A. Rogoyski, E.A. McLean, and G.J. Pert, *Opt. Commun.* **75**, 406 (1990).

[5] J. Nilsen and J.C. Moreno, *Opt. Lett.* **19**, 1137 (1994).

[6] H. Daido, R. Kodama, K. Murai, G. Yuan, M. Takagi, Y. Kato, I.W. Choi, and C.H. Nam, *Opt. Lett.* **20**, 61 (1995).

[7] T. Kawachi, K. Murai, G. Yuan, S. Ninomiya, R. Kodama, H. Daido, Y. Kato, and T. Fujimoto, *Phys. Rev. Lett.* **75**, 3826 (1995).

[8] D. Benredjem, A. Sureau, B. Rus, and C. M"ller, *Phys. Rev.* **A 56**, 5152, (1997).

[9] B. Rus, C.L.S. Lewis, G.F. Cairns, P. Dhez, P. Jaegle, M.H. Key, D. Neely, A.G. MacPhee, S.A. Ramsden, C.G. Smith, and A. Sureau, *Phys. Rev. A 51*, 2316 (1995).

[10] M.K. Inal and J. Dubau, *J. Phys. B* **20**, 4221 (1987).

[11] J.C. Kieffer, J.P. Matte, H. Pepin, M. Chaker, Y. Beaudoin, T.W. Johnston, C.Y. Chien, S. Coe, G. Mourou, and J. Dubau, *Phys. Rev. Lett.* **68**, 480 (1992).

[12] J.C. Kieffer, J.P. Matte, M. Chaker, Y. Beaudoin, C.Y. Chien, S. Coe, G. Mourou, J. Dubau, and M.K. Inal, *Phys. Rev.* **E 48**, 4648 (1993).

[13] W. Eissner and M.J. Seaton, *J. Phys. B* **5**, 2187 (1972).

[14] H.E. Saraph, *Comput. Phys. Commun.* **15**, 247 (1978).

[15] W. Eissner, M. Jones, and H. Nussbaumer, *Comput. Phys. Commun.* **8**, 270 (1974).

[16] M. Cornille, J. Dubau, and S. Jacquemot, *At. Data Nucl. Data Tables* **58**, 1 (1994).

Table I*a*. Excitation and de-excitation rate coefficients (in units of 10^{-11} cm^3/s) for level-to-level collisional transitions ($g \to u$, $g \to l$, $u \to l$ and $u \to 3d^1P_1$) and for elastic rate coefficients for the transitions between M_J =0 and M_J =1 sublevels within the l level, due to the isotropic and cold electron component of temperature T_1.

The subscripts *e*, *d* and *el* refer to excitation, de-excitation and elastic collisions, respectively.

	T_1 (keV)			
	0.2	0.3	0.4	0.5
$C_e\,(g \to u)$	1.60(-2)	1.24(-1)	3.31(-1)	5.84(-1)
$C_e\,(g \to l)$	3.36(-4)	2.43(-3)	6.38(-3)	1.13(-2)
$C_d\,(u \to l)$	5.82(1)	4.93(1)	4.41(1)	4.06(1)
$C_e\,(u \to 3d^1P_1)$	2.07(2)	1.92(2)	1.79(2)	1.69(2)
$C^{(1)}_{el}\,(l\,0 \leftrightarrow l\,1)$	9.99(-1)	7.73(-1)	6.07(-1)	5.14(-1)

Table I*b*. Rate coefficients (in units of 10^{-11} cm^3/s) for all considered collisional transitions, due to the directive and hot electron component of temperature T_2. The subscripts *e* and *d* refer to excitation and de-excitation, respectively. The results for elastic collisions are not shown because they are negligibly small.

	T_2 (keV)			
	2.0	3.0	5.0	8.0
$C_e(g \to u)$	2.36	2.46	2.33	2.06
$C^{(2)}_e\,(g \to l\,0)$	1.24(-1)	1.49(-1)	1.66(-1)	1.67(-1)
$C^{(2)}_e\,(g \to l\,1)$	3.39(-2)	4.48(-2)	5.83(-2)	7.13(-2)
$C^{(2)}_d\,(u \to l\,0)$	1.87(1)	1.46(1)	1.03(1)	7.13
$C^{(2)}_d\,(u \to l\,1)$	2.86(1)	2.56(1)	2.15(1)	1.69(1)
$C^{(2)}_e\,(l\,0 \to u)$	1.93(1)	1.51(1)	1.07(1)	7.40
$C^{(2)}_e\,(l\,1 \to u)$	2.72(1)	2.46(1)	2.12(1)	1.72(1)
$C_e\,(u \to 3d^1P_1)$	1.11(2)	9.72(1)	7.96(1)	6.44(1)

Table II. Populations of the upper level u and of the lower magnetic sublevels $l, M_J = 0, 1$ of the Ge^{22+} $J = 0$ - 1 lasing line, relative to the ground level g population, for various values of the electron temperatures (T_1, T_2). These results were obtained for an electron density 5.10^{20} cm^{-3} and for hot electron fractions $f = 0.1$ (upper entries) and 0.05 (lower entries). The ratio between the populations of the $l, M_J = 0$ and 1 magnetic sublevels is also shown.

	(T_1, T_2) (keV)				
	(0.2,3.0)	(0.3,5.0)	(0.4,5.0)	(0.4,8.0)	(0.5,8.0)
N_u/N_g	9.91(-4)	1.45(-3)	2.48(-3)	2.30(-3)	3.54(-3)
	5.16(-4)	9.62(-4)	1.97(-3)	1.86(-3)	3.10(-3)
N_{l0}/N_g	9.19(-5)	1.11(-4)	1.52(-4)	1.43(-4)	1.88(-4)
	4.74(-5)	6.80(-5)	1.10(-4)	1.04(-4)	1.51(-4)
N_{l1}/N_g	6.73(-5)	8.70(-5)	1.30(-4)	1.23(-4)	1.71(-4)
	3.45(-5)	5.52(-5)	9.82(-5)	9.40(-5)	1.43(-4)
N_{l0}/N_{l1}	1.36	1.28	1.17	1.16	1.10
	1.37	1.23	1.12	1.11	1.06